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QUATERNARY EVOLUTION, MORPHOLOGY, AND SEDIMENT DISTRIBUTION, WESTERNPORT BAY, VICTORIA

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ABSTRACT: The complexity of Westernport Bay springs from its overall morphology which is controlled mainly by bedrock distribution, the relative lack of freshwater and sediment input from the hinterland, the dominance of tide-driven sediment movement patterns, and long-term net landward transport and deposition of sediment with the concentration of the main tidal flats in the head of the Bay. Westernport is strictly an embayment, not an estuary, and differs markedly from neighbouring Port Phillip and many embayments elsewhere.

Three lines of evidence portray the physical and sedimentological variability of Westernport Bay, namely:

(a) its Quaternary evolution in which four phases are recognized, showing an interplay between tectonics, erosion, deposition and sea level changes, including evidence for higher Holocene sea level that at present;

(b) the morphology of the present Bay, with the recognition of rapid variation between morphological units within eight major morphological systems, shown at a scale of 1:50,000, and including: 1. Beaches, Rock platforms, 2. Salt Marsh Zone, 3. Mangrove Zone, 4. Inshore Marginal Sandy Zone, 5. Intertidal Flats and Banks, 6. Offshore Banks and Shoals. 7. Embayment Plains, 8. Tidal Channel Systems;

(c) the distribution of bottom sediment types, shown at a scale of 1:125,000. An overall inward-fining sediment gradient is consistent with net landward re-working of relic sediment, with only minor contributions from the hinterland prior to artificial drainage.

Both morphology and sediment distribution indicate specific bedload transport paths for ebb-flow and flood-flow, particularly along the channels. Landward transport also of suspended sediment is thought to have been responsible for the accretion of the very extensive intertidal sedimentation zones which occupy about 35% of the area of the Bay.

INTRODUCTION

A highlight of Westernport Bay is the greater complexity of its evolution, morphology, dynamics, and sediment movement, compared with Port Phillip, and many other embayments and estuaries. Its variability and complexity is characteristically matched by variability in biological and other features.

Lying in a mildly tectonic region, Westernport is a drowned embayment, in which present-day processes are responding to Quaternary changes. The general Holocene sea-level rise, followed by a minor relative fall, has imposed some of the interacting morphological and sedimentation characteristics of Westernport Bay, both external such as the entrenched river and terrace systems, emergent depositional features and raised rock platforms, and also internal characteristics, particularly the submarine topography and the provision of sources of relic sediment for re-working within the Bay.

Among the unusual factors controlling the behaviour of Westernport are:

—Its morphology, principally controlled by distribution and erosion of bedrock, rather than by sediment-constructed features as found in more typical estuaries and barrier-lagoon-tidal flat systems. As a result, its behaviour is dominated by the elongate, linear channel systems which open through a cliffed coastline to the high wave-energy zone of Bass Strait, modified by the smaller, and younger Eastern Entrance.

—The lack of significant fresh water and sediment input from the hinterland, except from the Bass River, and the consequent absence of any significant mechanism for net outward sediment

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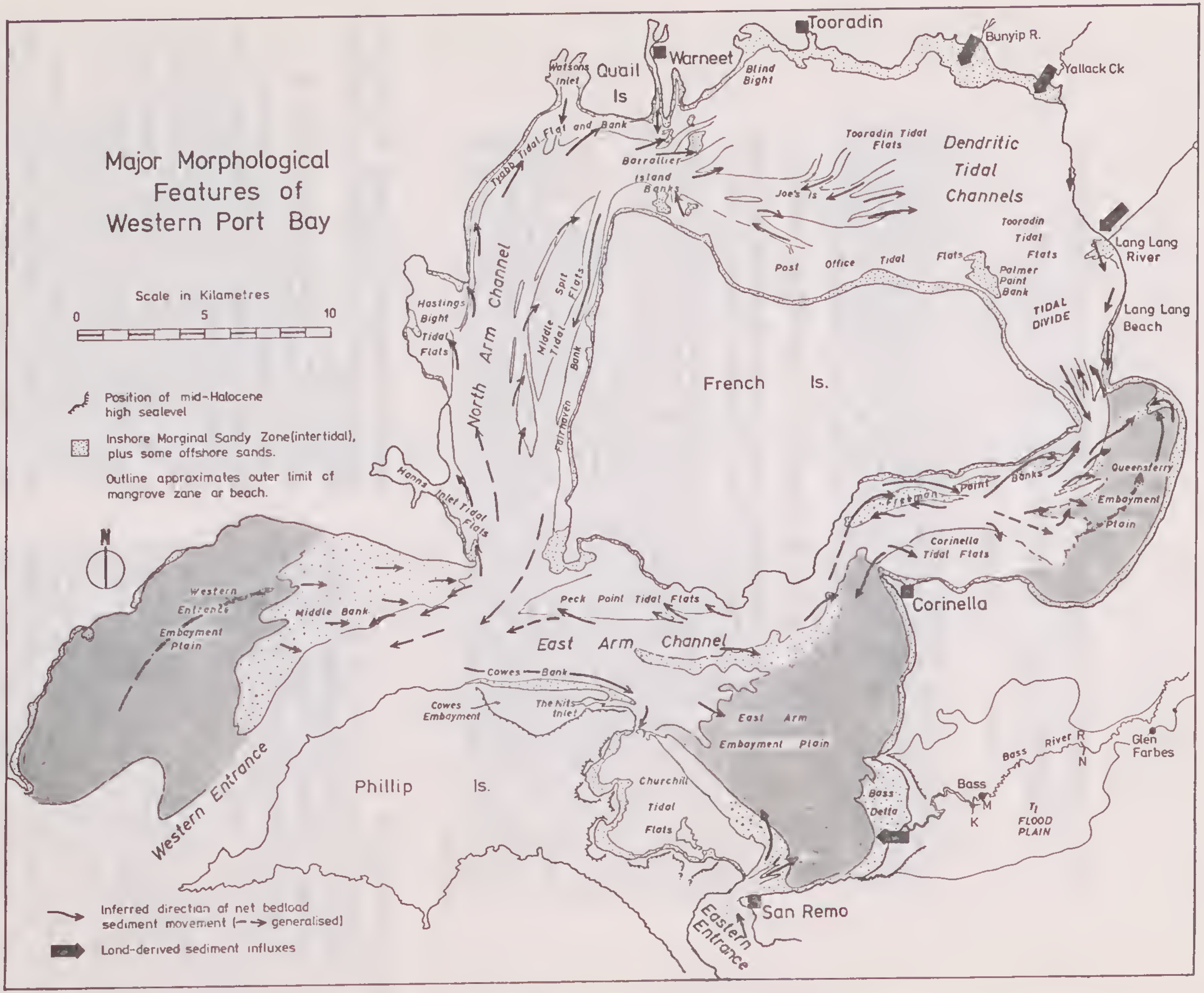

FIG. 1—Major morphological features of Westernport Bay.

transport. Marked sedimentation changes are now occurring locally, however, as a result of the recent artificial drainage of the Koo-wee-rup Swamp, and probably of forest clearing.

—The major role of tidal currents in transporting sediment, and the general absence of sediment drive resulting from strong salinity gradients. Large areal differences in tidal range and velocities and complex differences in ebb and flood movement paths control many of the sedimentation patterns, with the deeper parts of the Bay containing the coarsest sediment.

—The orientation of the Western Entrance and major arms of the Bay in relation to the dominant directions of wind-generated wave movements (essentially between 180° and 360°).

—The availability of a range of relic and other sediment types and sizes, both terrigenous sediment and biogenic carbonate.

—The inward-fining sediment gradient, and the concentration of the major depositional zones in areas marginal to the channels and in the head of the Bay, which are consistent with net landward transport.

In particular, these characteristics differ from Port Phillip, in which the contrasting seaward-fining sediment gradient is controlled by increasing depth, supply of sediment from streams, and the relatively low tidal range and tidal velocities (Beasley 1966, Bowler 1966, Link 1967). Westernport is a tidal embayment and lacks the characteristics of an estuary (Schubel 1971).

Three lines of evidence portray the physical and sedimentological variability and complexity of Westernport Bay:

(a) Quaternary evolution, with its interplay between sea-level changes, tectonics, erosion, and deposition.

(b) Morphology of the present-day Bay (Fig. 1), divisible into a large number of individual morphological units whose distribution and sediment type are sensitive to variation in controlling processes.

(c) Distribution of bottom sediment, with the zone boundaries for different textural types often extrapolated on the basis of the distribution of appropriate morphological units. Broad, but distinct net sediment transport paths are also delineated.

METHODS

Colour aerial photographs were the basis for the interpretation of the morphology, particularly for the northern half of the Bay (mainly from the 1973–74 Westernport Project 1106, at an approximate scale of 1:15,000). Basic ground experience for interpretation of the Quaternary evolution and morphological relationships was provided by studies involving detailed mapping in the southern part of the Bay, carried out by the Department of Geology, University of Melbourne, from 1970–1973 by Power (1971), Tickell (1971), Brennan (1972), Gray (1972), Walter (1973), and Walker (1973). Elsewhere, a limited number of ground checks has been made.

The criteria used to delineate morphological units included: (a) surface textures of sediments such as the drainage patterns and the patterns of difference of relief, (b) shapes and contrasting elevations of sediment bodies, (c) vegetation cover, both uniformity of type and relative density. The deeper tidal channels were identified by absence of light return, which also, with the exception of the shoal areas, prevented differentiation of morphological features. The photography was carried out mainly at high tide, which lessened the observable detail over much of the area.

The morphological interpretation has been compiled on four 1:25,000 map sheets (Marsden & Mallett 1974) and reduced to 1:50,000 herein (Fig. 2, map in back pocket).

Approximately 200 bottom sediment samples were collected by a mechanical grab, mostly from September 1973 to March 1974, but some samples from the earlier studies were also incorporated. The majority of the 1973–1974 sample stations were chosen as part of the Fisheries and Wildlife Division Zoobenthos Survey, either by random selection or at intersections of the 1 km grid. Because of the close relationship between morphology and sediment type, other sediment sample locations were based on the morphological interpretation. Sample locations are shown in Fig. 7.

For each sample, after oxidation of organic matter, size analysis of sand was carried out by sieving, and pipette analysis of the mud fraction was undertaken to differentiate silt and clay. Separation of the terrigenous and the biogenic carbonate fractions was not attempted. For each sample, sand, silt, clay, and mud (silt plus clay) percentages were computed. Additionally, mean grain size, sorting, skewness and kurtosis (Folk 1968) were calculated on data from the individual sand fractions plus the silt fraction, re-calculated to 100%. The clay fraction was omitted from the calculation (see later under *Sediment Distribution*). The data was presented in detail in Marsden and Mallett (1974).

Nomenclature of sediment types was based on relative proportions of sand, silt and clay (Shepard 1954), (Figs. 4, 9). The sampled distribution of sediment types was used, in conjunction with the

TABLE 1. QUATERNARY EVOLUTION OF THE WESTERNPORT SUNKLAND.

PHASE	POSSIBLE TIME *(Years B.P.)*	SEALEVEL *(Relative)*	GENERAL GEOLOGICAL CONTROL OR RESPONSE	FLUVIAL RESPONSE *(Bass River)*
4C		? Small-scale/local changes in level, storminess etc.	Present-day fluvial and coastal modifications, including swamp drainage and forest clearing.	Deposition of modern point bars etc. (by reworking of T_2 etc.).
		PRESENT-DAY-LEVEL		
4B		*Regressive phase*	Progradation of intertidal zones. Abandonment of depositional and erosional features of high sea-level.	Entrenchment into: – T_2 terrace, – high level saltmarsh etc., – emergent zones of Sbi, and underlying T_1. Abandonment of meanders, lower Bass River.
	Holocene – – 5000 to 6000	MAXIMUM – 1 to 2m above present level	Start of rapid progradation of barriers, beach systems.	
4A		*Flandrian Transgression*	Swamp development. Drowning of relic topography and sediments; drainage disruption. Mesozoic increasingly important sediment source.	Deposition of T_2 sediments.
	Late Pleistocene 16,000	RISING	Start of marine re-working of sediment. Some net inward movement, including to inter-tidal zone.	Gravels, sands of Western Entrance sub-strate (older in part?).

START OF POST-GLACIAL SEALEVEL RISE AND

3	18,000 to 20,000 *Pleistocene* Kosciusko (Würm) Glaciation.	LOW Possibly to −27m.	Erosion: sediment transported to beyond present shore. Aeolian activity. Minor tectonic movement – Bass, Almurta Faults.	Entrenchment of T_1 terrace. General position of trunk tidal channels and embayment plains fixed.
2	*Pleistocene* ? Last Interglacial (or earlier). 125,000	HIGH? (relatively, but evidence lacking for levels as high as at present).	Extensive fluvial deposition (limits beyond present shore). Tertiary sediments (upthrown areas) important sediment source.	Deposition of T_1 sediments. Northern part of sunkland: - Heath Hill Silt, - Cardinia Sand, - Clays (Hastings area)?
1	*Early Pleistocene ?*	LOW? (relatively).	Main fault movements. Start of erosion – stripping, and sediment transport to beyond present shore.	Establishment of major drainage systems.

TABLE 1. QUATERNARY EVOLUTION OF THE WESTERNPORT SUNKLAND.

INSHORE MARGINAL SANDY ZONE AND OTHER ZONES			MARINE EROSION RESPONSE
Sedimentation Influx Area (Bass Plain - Sbi sheet)	*Dominant Longshore Transport (Cowes Embayment)*	*Isolated Inshore zones, landward transport, and relic sediment zones*	
Marine erosion of saltmarsh etc. in places Degradation of present beach ridge.			Rock platform, cliff cutting at present level.
7. Progradation of saltmarsh. 6. Beach ridge succession. (R_1 to R_9). 5. Sbi sand sheet. ("delta progradation" offshore). *Regressive* ↑	5. Eastward transport persisting. 4. Progradation, saltmarsh and mangrove. 3. Succession of spits (S_1 S_2 S_3) and lagoons. 2. Sand "sheet" *Regressive and prograding* ↑	Progradation of saltmarsh, mangrove zones and of isolated and embayment-head tidal flats.	Successive regressive scalloping of South Bass cliff-line etc.
4. Sbi sand sheet. 3. Oldest beach ridge (R_0). 2. Transgressive marine shell bed. 1. Swamp clays. (more extensive in north - Kooweerup Peaty Clay and Dalmore Clay). *Transgressive* ↑	1. Beach ridge development. Isolation of Rhyll Swamp. Possible transgressive basal sediments?	Isolated beach deposits, beach ridge, saltmarsh deposits etc. at high level. (e.g. northern Phillip Island and French Island). Drowning of Cranbourne Sand areas, northwestern part of bay. ?Intertidal, swamp etc. deposits of transgressive phase.	Opening of Eastern Entrance. Cutting of high-level rock platforms, cliffs. Development of Cowes Embayment (now largely filled). Start of erosional shoreline development.
PRESENT—DAY MARINE CYCLE IN WESTERN PORT BAY			
		(Cranbourne Sand and associated aeolian topography).	?
			(Possible cliff development at some stage for Holocene re-occupation).

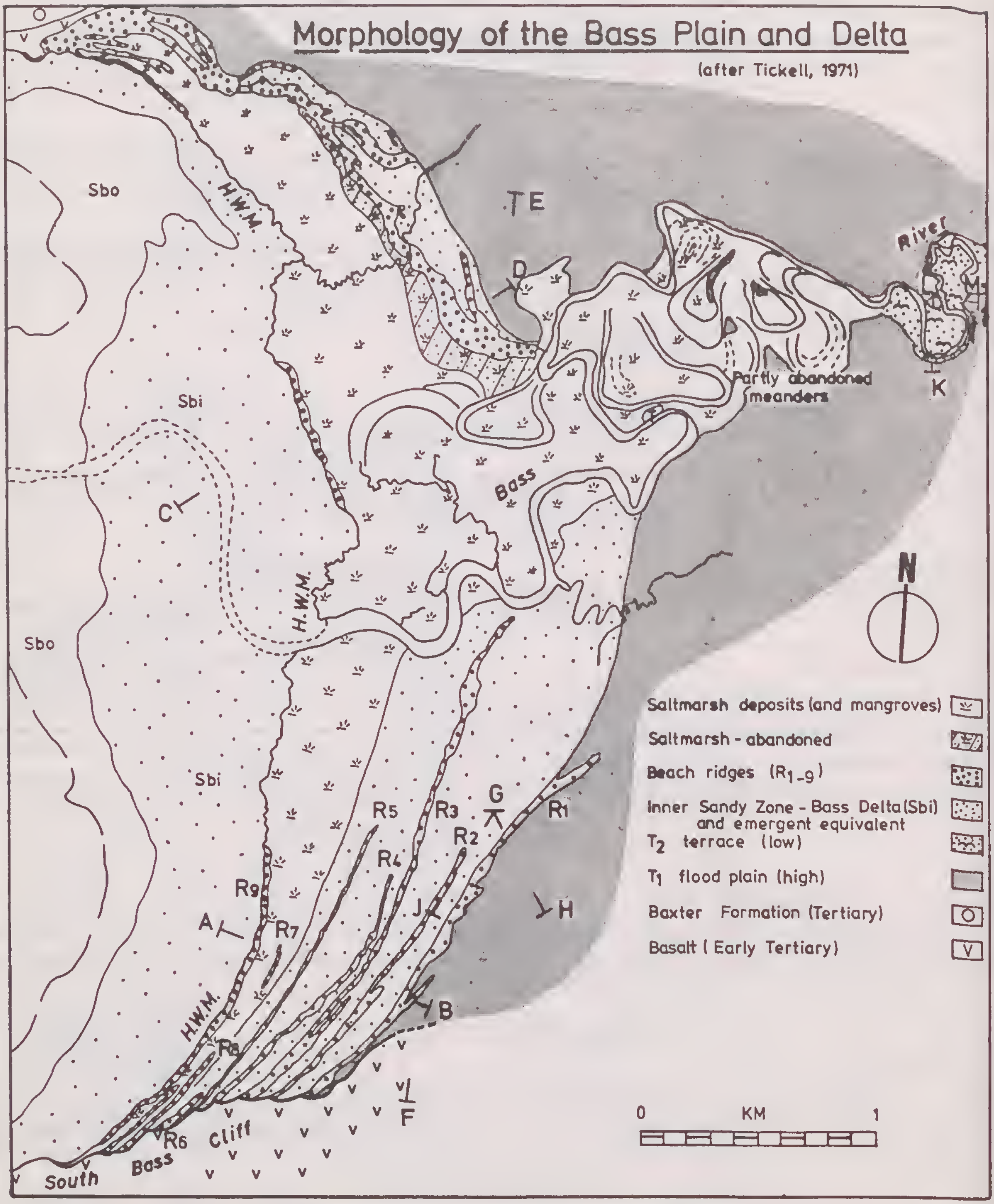

FIG. 3a—Morphology of the Bass Plain and Delta.

distribution of morphological units, to construct a generalized interpretative map of the distribution of sediment types within Westernport Bay, given at a scale of 1:50,000 in Marsden and Mallett (1974) and included herein at a scale of 1:125,000 (Fig. 7). This must regarded as a preliminary interpretation in the light of the need for close sampling in such a varied system.

QUATERNARY EVOLUTION

INTRODUCTION

Morphology, bathymetry and sediment distribution in Westernport Bay are partly functions of the drowning of pre-existing topography by sea-level rise from the end of the Pleistocene and during the Holocene, followed by a relatively minor, recent fall of 1 to 2 m. Valuable descriptions of many of the onshore and littoral physiographic features of the sunkland have been given by Hills (1942), Keble (1950) and Jenkin (1962). A need exists for a comprehensive historic framework relating these to the complex Quaternary history of the Westernport Sunkland, without which the interpretation of present-day features and processes is limited.

The generalized and tentative framework presented in Table 1 is based largely on work carried

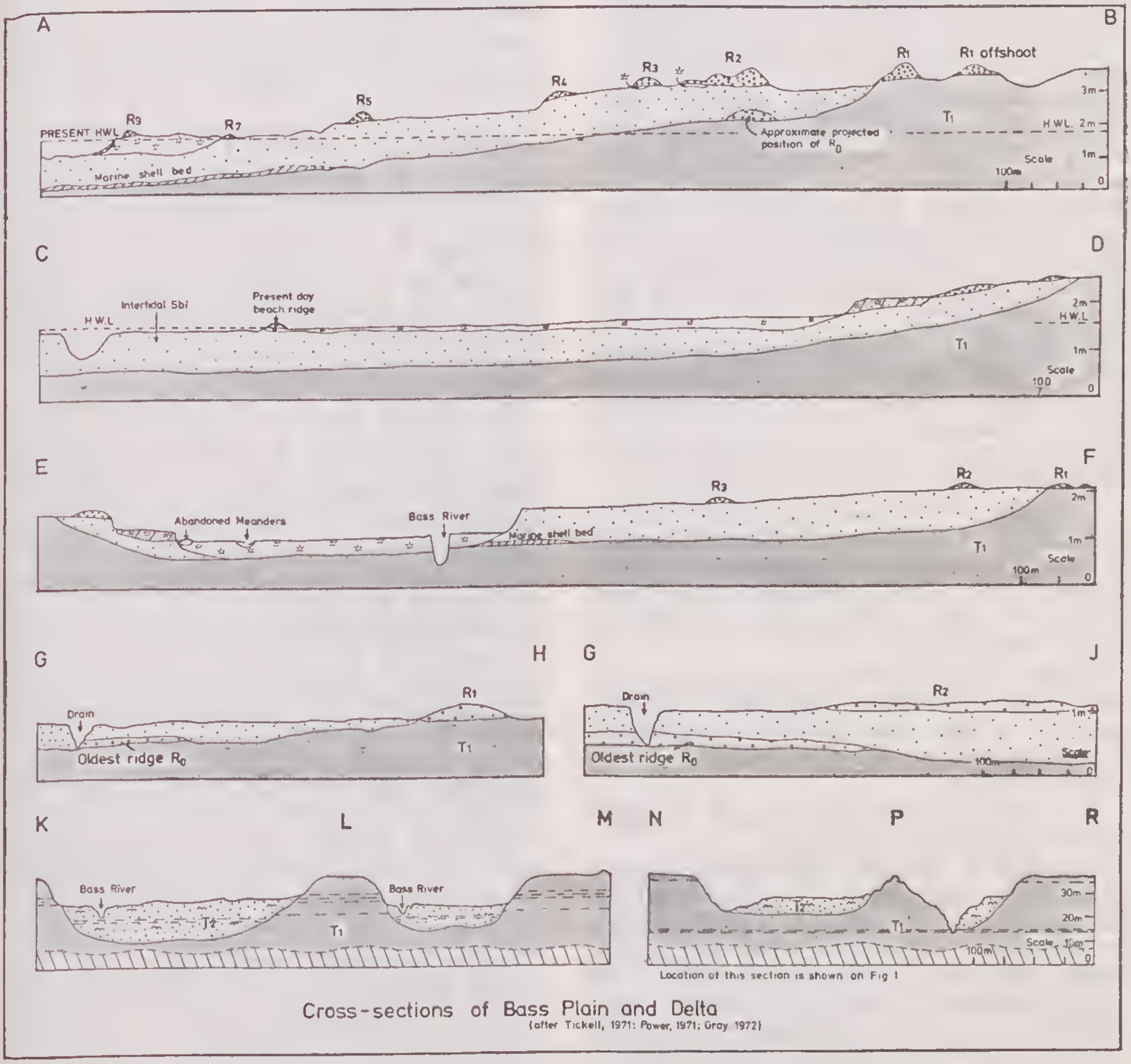

FIG. 3b—Cross-sections of the Bass Plain and Delta. Legend as for Fig. 3a.

out by the Geology Department in the south-eastern part of the Westernport Sunkland. This region was chosen as it provides important evidence of sea-level changes (tectonic or glacio-eustatic), the Bass River system in particular demonstrating the link between a succession of fluviatile floodplain terrace deposits, and Holocene erosion and marine sedimentation sequences. Correlations beyond the Westernport region have not been attempted.

Four phases of Quaternary history are recognized, the elapsed time between which may have been substantial, and possibly unrepresented in the sequence as known at this stage. The Pleistocene succession is little known, marine deposits being notably either absent or not yet recognized.

The Bass succession (Figs. 3a, b) serves as an introduction to the Quaternary history of Westernport:

Phase 1. Faulting and drainage initiation: downcutting of the sunkland drainage systems, possibly during relatively low sea level (? Early Pleistocene).

Phase 2. Extensive fluviatile deposition: Pleistocene deposition of the extensive Bass River floodplain (T_1), possibly partly in response to a relatively higher sea level (perhaps the last Interglacial).

Phase 3. Erosion: entrenchment by Bass River into the higher terrace T_1, at a time of low sea level, possibly correlated with the Kosciusko (Würm) Glaciation.

Phase 4. Holocene marine phase: rising but fluctuating sea level.

4*a*. Rising sea level and progressive drowning of the Bay (?18,000 years B.P. [Late Pleistocene] to 5000-6000 years B.P.), deposition of fluvial sediments (T_2) in the entrenched valley; transgression of marine sediments over the old T_1 surface (Bass Plain).

4*b*. Fall of sea level from maximum to present level (?since 5000–6000 years B.P.), entrenchment by the Bass River into the lower terrace T_2, progressive retreat of the shoreline to its present position.

4*c*. Present-day small adjustments of either sea level, climate, etc., often local.

Migration of shoreline and marginal marine zones and onshore responses have provided the data for Table 1, in which sea level fluctuations and geological factors are correlated with marine erosion, with fluvial response (Bass River), and with the response of beach and intertidal zones, particularly the Inshore Marginal Sandy Zone (Fig. 1). Evolution of variants of the latter may also be correlated as firstly a sediment influx zone (Bass delta area), secondly a zone of dominant long-shore drift (the Nits-Rhyll Swamp-Cowes Bank), and thirdly isolated inshore zones, tidal flats, and zones of relic sediment.

Strict time-equivalence across the columns of Table 1, and strict upward sequence, is not always implied. Correlations are necessarily broad. The Table underlines many unresolved questions: data from both surface and sub-surface sediments, controlled by radiometric dating, is required to relate satisfactorily sea level, tectonic, erosional, fluvial and marine successions.

Phase 1: MAJOR FAULTING AND INITIATION OF DRAINAGE SYSTEMS OF THE WESTERNPORT SUNKLAND

Following deposition of the Baxter Formation, towards the end of the Tertiary much of the region was presumably of low relief and relatively flat. Generally, the Sunkland development has been controlled tectonically, by movements along rejuvenated major bounding faults, and on faults, regarded as early Pleistocene or late Tertiary in age, within the Sunkland itself. Younger, if only relatively minor, tectonic movements and seismicity have also been recorded in the region up to the present day (Underwood 1972, Bishop & Cresswell 1972). The main movements produced the relief for establishment of the major drainage systems, and structural control of the drainage patterns and other physiographic features (Spencer-Jones et al. 1975).

The present Bass River, the largest natural influx into the Bay, is structurally controlled. It runs generally northwesterly in its headwaters reach on the upthrown block of the Bass Fault, but after crossing the Almurta Fault at Loch, its sharp deflection to a southwesterly course has been dictated by the line of the Bass Fault. Until Glen Forbes, it is restricted within a narrow plain cut between the Heath Hill and Almurta Blocks. As the relief of the Heath Hill Block fades away southwesterly, a further distinct wide reach up to 7 km wide is developed from Glen Forbes to Bass. Between Bass and the river mouth (Fig. 3a), two distinct reaches occur: a zone of large, partly-abandoned meanders, then the Bass delta. The early Quaternary Bass River however undoubtedly continued in a broad valley further west beyond the present mouth, to join other systems draining the region through the present Western Entrance. Although sea level must have been relatively low, no link with any glacial low-level has yet been shown; the extent of tectonic uplift is also unknown. Significant volumes of both fine and coarse sediments, probably composed mainly of reworked Baxter Formation, were transported into the areas now occupied by the main tidal channels, the

Western Entrance and the offshore areas of Bass Strait.

Phase 2: EXTENSIVE FLUVIATILE DEPOSITION —RELATIVELY HIGH SEA LEVEL

The Bass River T_1 sediments are now overlain by Holocene fluvial and marine sediments and are therefore regarded as Pleistocene. In the simplest view, they could be correlated with higher sea levels of the last Interglacial (125,000 years B.P.) but there is no real basis for this. Elsewhere in Victoria, Jenkin (1968) has indicated sea levels of up to 15 m higher than at present, but no evidence for such higher levels is known in the Bass area. On the contrary, the fluvial T_1 deposits extend beneath the Inshore Marginal Sandy Zone (*Sbi*) sediments of the Bass delta (Figs. 3a, b) and appear to form the morphological base for the present East Arm Embayment Plain (Fig. 1).

A thickness of up to 15 m of T_1 sediments was deposited as an extensive flood plain, under conditions of greater stream discharge than at present. Where their base is seen, they lie on an erosion surface cut in Mesozoic sediments. However, the sequence was derived mainly from erosion of Baxter Formation sediments, and only minor remnants of these now remain on the upthrown fault blocks. Contributions from Mesozoic sources were relatively minor. Source is indicated by the textural characteristics of the T_1 sediments (Fig. 4). In composition, the T_1 lithologies are essentially quartz-clay mixtures, reflected in the dominant size types which are clay, silty clay, and sand-silt-clay, but ranging to gravel and sand. They are poorly sorted, typically comprising up to 25-30% sand with clay:silt ratios of 2:1. Silt is often not significant. Clear granitic (and other) quartz characteristics of Tertiary sediments generally forms 90% of the sand-size material, with only minor feldspar (usually less than 5%) and rare lithic fragments of Mesozoic sediments. The sediments are well-bedded, variable, well-consolidated and often mottled, with unlaminated grey clay the most common lithology. They appear to be overbank deposits with lesser channel and point bar deposits, suggesting by-passing of the coarser sediment load by down-channel transportation, beyond the present shore.

Although the T_1 samples show a broad scatter, a number of those which plot in the general field of T_2 (Fig. 4) were taken from localities near the headwaters of the Bass River. Their textural similarity to T_2 sediments is probably due to their deposition after exposure of Mesozoic source rocks, followed by downcutting and headward erosion.

Fluviatile deposition, probably contemporaneous, occurred elsewhere in the Westernport Sunkland. Jenkin (1962) regarded the Cardinia Sand as fluviatile channel and levee deposits associated with alluvial fan and floodplain deposits of streams from the northern highland areas and brought down to the Koo-wee-rup Basin-Lang Lang area. Thompson (1974) has shown that silty clays and silty sands (with occasional gravel layers) of the Heath Hill Silt form an extensive, continuous sheet between 15 and 45 m thick. This extends from the Heath Hill area westwards across the Koo-wee-rup plain, where the sediments tend to become more clay-rich. It is regarded as originating from widespread and possibly prolonged deposition from the major fluviatile systems of the northern part of the Sunkland, which were cut mainly into Baxter Formation but occasionally into the Older Volcanics. Deposition occurred both in the incised marginal valleys of restricted width, and also over the more extensive areas of coalesced floodplains.

A widespread sheet up to 6 m thick of grey clays and sandy clays occurs northwards from Stony Point, both offshore in the North Arm, and also onshore, especially near Hastings and as far north as Watsons Inlet. Its relationships and age are unknown but the clays may be essentially lacustrine and broadly equivalent to the Heath Hill Silt (Barton 1974).

Phase 3: EROSION—RELATIVELY LOW SEA LEVEL

Entrenchment of a valley into the T_1 floodplain

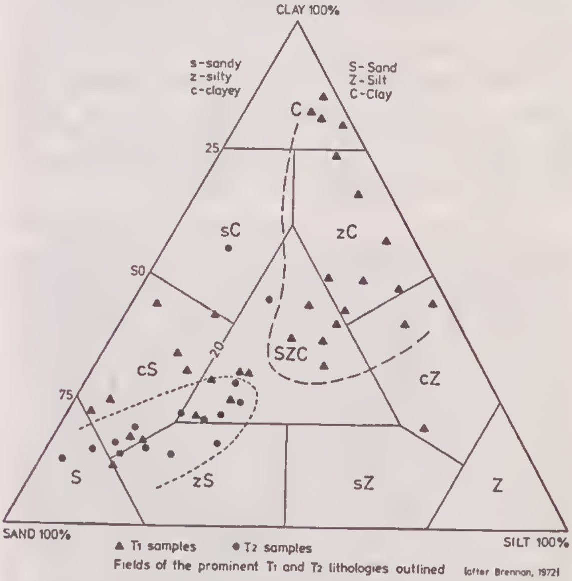

FIG. 4—Textural composition of the T_1 and T_2 sediments of the Bass River.

occurred before Holocene deposition. It is reasonable to relate this to the immediately previous sea-level fall during the Kosciusko (Würm) Glaciation (maximum—18,000 to 20,000 years B.P.), but again, no real evidence of the date of entrenchment exists. Tectonic factors also cannot be discounted, and have probably been at least locally important throughout the Quaternary, as indicated in the profile of the T_1 terrace between the Bass and Almurta Faults. Here, the T_1 surface increases in height by about 5 m relative to both the surface of T_2 and to river level, suggesting uplift and/or warping of the Almurta Block some time before deposition of T_2.

The valley entrenched into T_1 was relatively narrow, averaging 100 m in width and about 8 to 10 m in depth. The composition of the later filling (T_2) is distinctly different, indicating that the eroded T_1 material was moved further out into the Sunkland. The floor of the East Arm Embayment Plain, although somewhat modified, by younger sediments, also shows some entrenchment (Fig. 2), indicating that sea level was lower than the outer edge of the embayment plain.

Other detritus was also transported into outer areas of Westernport Bay and beyond, available for subsequent re-working, including fine sediment from the Mesozoic, and quartz and clay from Tertiary (Baxter Formation) sedimentary rocks. From the nearby flanking areas of Older Volcanics, both clays and fine and coarse basalt rock fragments would have been transported down relatively short, steep paths into the main channels, the Western Entrance and along the present Bass Strait coast. Thus prior to the present-day (Holocene) sedimentation cycle, a diverse relic sediment population, both in composition and texture, could be expected on the exposed walls and floor. Accompanying weathering of the flanking bedrock areas also developed potential sedimentary material.

During this low sea-level phase, the irregular aeolian sand ridges and sheets of the Cranbourne Sand were formed in the north of the Sunkland, possibly by re-working of Baxter Formation by both wind and water. A well-defined belt runs from Frankston to the northern shores of the Bay near Quail Island, and other occurrences are found on the northwestern part of French Island, and also near Lang Lang. Connection probably existed across the low-lying northwestern corner of the Bay, from the Quail Island area to French Island. Hills (1942) suggested that the aeolian activity reflected aridity, but interpretation is hampered by the diachronous nature of the sands. Some of the sheet-like areas near Warneet, for example, are very young, being re-distributed over Holocene swamp deposits (Cass 1973).

Phase 4: HOLOCENE MARINE PHASE—RISING BUT FLUCTUATING SEA LEVEL

This is the modern marine cycle in Westernport Bay, throughout which a complex continuum of processes has been operative to the present day. It has been arbitrarily divided into (4A) a period of sea-level rise (Flandrian Transgression), (4B) high sea level followed by a minor sea-level fall, and (4C) present-day small-scale variations, modifying the morphology and sediment distributions.

On evidence from elsewhere (Gill 1971) the post-glacial Flandrian Transgression started from 18,000 years B.P. near the end of the Pleistocene, and occurred fairly rapidly to its maximum about 6000 years B.P., which in Westernport Bay was 1 to 2 m above present HWM. In such a closely faulted area, height consistency of the residual evidence is not likely to be found.

4A—Rising Sea Level and Progressive Drowning of the Bay

Drowning of the actual Bay through the Western Entrance started about 10,000 years B.P., and shaping of the main channels by tidal scour began immediately. Decline in fluvial activity allowed progressive winnowing and differentiation of relic and weathered material, particularly by net landward transport of finer fractions. Lithologies such as the pebble and cobble conglomerates, now found by coring in the channel substrate, may therefore have various origins, but are probably mainly fluviatile and therefore at least 10,000 to 15,000 years old (Spencer-Jones et al. 1975). The present sediment distribution, with its overall landward-fining gradient, has its basis in processes operative from this time.

(i) *Drowning of Relic Topography and Erosion*

Modification of the sub-strate morphology occurred during sea-level rise. As well as debris stripping, some rocky features undoubtedly developed which have since been drowned. The development of the present rocky coastline is referred to later.

Inlets marginal to the main tidal channels now started to develop their final morphology, which, together with their aspect, controls the nature of their subsequent sedimentary filling. Along the northern coast of Phillip Island for example, erosion resulted in inlets, backed by cliffs and platforms. Churchill Inlet between Rhyll and Newhaven developed a broad gently-shelving sheltered floor where clayey sediments accumulated. In contrast Cowes Embayment between

Cowes and Rhyll (Fig. 5b) must have been relatively deeply cut and is now filled with sand. A seismic refraction survey conducted by the geophysics group of the Geology Department (Fig. 5a), showed that the depth to the substrate (?Older Volcanics) increases relatively rapidly northwards, from near zero to about 20 m near the present coast, over a distance of little more than 1 km (L. Thomas, pers. comm.).

Many marginal areas of Westernport were of low relief and low gradient, and underpinned by rocks of relatively low erosion resistance. Here the morphological effects of sea-level rise were variable and generally cliff and platform cutting less important, particularly in the inner embayment-head areas.

Drowning of parts of the aeolian Cranbourne Sand areas occurred at this time, developing large inlets in the northwestern segment of the Bay and supplying unconsolidated relic sand.

Extensive Holocene swamp development also occurred, in valleys leading to the coastal plain areas, and especially in the northern part of the Sunkland (Koo-wee-rup Swamp). The latter must owe its origin and maintenance mainly to the effect of rising sea level on the water table levels, although climatic change (Hills 1942) and tectonic tilting (Jenkin 1962) have also been invoked.

Drowning of the low-gradient East Arm Embayment Plain probably occurred rapidly as soon as rising sea level attained its outer rim, partly accounting for the relative lack of sandy sediment within the embayment plain area itself. Sands started to develop only at or near the time of high sea level, presumably after the position of the Inshore Marginal Sandy Zone had become relatively stabilized. The initial development of the main cliff-line forming the southern margin of the Bass Plain (South Bass cliff) probably occurred at this stage, together with some slight marine erosion of the inundated margin of the T_1 surface (Fig. 3b).

(ii) *Fluvial and Inshore Zone Response—Bass Plain Area*

In most marginal areas of Westernport few effects of sea-level rise are now apparent. The importance of the Bass Plain region lies firstly, in the presence of Holocene intertidal and beach sediments related to both rise and subsequent fall of sea level, and secondly, in linking these with contemporaneous onshore processes, including fluviatile deposition of the T_2 terrace (Figs. 3a, b).

Phase 3 entrenchment of the T_1 terrace produced a lower, relatively narrow valley, with a maximum width of 200 m decreasing to 80 m in the upper reaches. The infilling Holocene T_2 deposits lie on T_1 material or occasionally on Mesozoic rocks. They contrast strongly with the T_1 sediments in being much more homogeneous and unconsolidated. Light brown to grey sands and muddy sands occur mainly as point bar and channel deposits within the restricted flood plain, indicating that most of the suspended load was carried down-stream, to the outer Bass delta (*Sbo*—Fig. 2), to the East Arm Embayment Plain and to other offshore areas. Rare overbank deposition on to the surface of T_1 occurs during major floods at the present day, possibly from increased run-off following forest-clearing.

Compared with the sediments of T_1, the muddy and silty sands of T_2 are texturally more uniform with distinctly less fine material, particularly the clay-size fraction. They contain between 50% to 85% sand, and the clay:silt ratio ranges typically from 2:1 to 1:1. The textural fields of T_1 and T_2 sediments are quite distinct (Fig. 4). The sands are typically fine to very fine with the mean size (based on sand and silt fractions) in the range of 0·070 to 0·140 mm. Although coarser on the average than T_1 sediments (mean sizes typically about 0·040 mm), their lack of gravel and coarse to very coarse sand is more pronounced. Compositionally they are distinguished by lower percentages of clay minerals, a sand fraction with distinctly more feldspar (15-30%), more grey lithic fragments of the Mesozoic sandstones (up to 5%) and mudstones. Correspondingly the quartz content of the sand fraction is lower (about 70-75%), and this distinguishes the T_2 sediments. These contrasts strongly indicate a marked increase in supply from the Mesozoic bedrock relative to Tertiary sediments, due partly to the earlier stripping of the upthrown fault blocks. The young hillwash material and the limited alluvial fans and aprons derived from the Mesozoic (Spencer-Jones et al. 1975) have similar compositions but are less differentiated by transport processes.

The marine sequence (Figs. 3a, b) was deposited on the slightly-eroded, shelving T_1 surface (or partly on grey swamp(?) clays overlying T_1 formed in response to rising sea level). The onshore part of the marine sequence is thin and wedges out about 1 to 1·5 km inland. The lowest unit is a sandy coquina (shell bed) about 15 to 30 cm thick, found offshore and also extensively onshore, north and south of the Bass River, at a depth of about 1·2 m. It contains well-packed bivalve shells, some 15% of which are still paired, together with lesser numbers of gasteropods, in a matrix of sand typical of that of the present-day offshore *Sbi* zone. *Anadara trapezia* is common.

Tidal and wave action in the intertidal zone during transgression over a cohesive substrate appears to have been the mechanism for the concentration and spreading of the shells, many of which have not been transported far.

Landward migration of the Inshore Marginal Sandy Zone with rising sea level deposited a thin sand sheet which, near its shoreward transgressive limit, has over-ridden the oldest (R_0) of a preserved succession of sand and gravel beach ridges. The majority of these overlie the sand sheet and hence belong to the subsequent regressive sea-level phase. Continuity of the sand sheet with the present-day Bass delta influx deposits (*Sbi*) shows that it owes its origin to both the transgressive and regressive phases. However, no structural or lithological distinction between the two phases can be made within the sheet, which is a homogeneous sand showing no bedding or other structures. These characteristics result from slow deposition combined with continuous re-working and bioturbation in the shallow intertidal zone.

At the time of deposition the offshore *Sbi* sands and the fluvial T_2 sediments were in physical continuity. The genetic relation of the sand (*Sbi*) to the T_2 sands of the Bass River is shown by their very similar grain size distributions and virtually identical median grain size (in the fine sand range, approximately 0·13 mm). The only minor textural differences are those to be expected of typical T_2 sediment subjected to winnowing in the intertidal zone, which would include clay removal (sand content of *Sbi* averages 90-95%), and very good sorting values. Compositional similarity to T_2 sediment is even more striking: typically 75% quartz, 10-20% feldspar and 5% lithic fragments of Mesozoic rocks. Although most of the feldspar is derived from the Mesozoic source area, the presence of small amounts of microcline in the modern *Sbi* sediments hints at a possible contribution from the Woolamai Granite through the Eastern Entrance.

4B—High Sea Level, and Subsequent Fall

(i) *Evidence for Higher Sea Level*

Evidence for mid-Holocene high sea level occurs widely in Westernport, and indicates a maximum height above present high-water level of about 1·5-2 m. When dating becomes available, apparent height variations between localities may be resolved as time-dependent. However, in Westernport heights may have been influenced by tectonic activity and also by regional sea-level fall. The time of maximum sea level is taken as 5000-6000 years B.P. (Gill 1971).

The time of the opening of the Eastern Entrance is unknown but must have been at or near high sea level, as the elevation of its original floor was well above that of much of the adjacent floor of Westernport. The relative youth of the entrance is further attested by its narrowness despite strong tidal scour. Detectable changes in the configuration of the channel occurred between the time of the surveys for the old and new bridges across The Narrows (1910 to 1963), and scour by coarse gravels has been observed in some of the deep parts of the channel (Ollier & Bowler 1963). The sharp truncation of the clay-rich Churchill Tidal Flats by channels and bars of the small, sand flood-delta, which is relatively newly-developed inside The Narrows, provides longer-term evidence. Breaching is thought (Edwards 1942) to have been assisted by marine back-cutting from Bass Strait from the line of the Kongwak Fault, developing the entrance along a short valley running south from the San Remo Horst. The Woolamai Granite was left as residual, as its rate of northward retreat was relatively low.

Other marine erosion evidence for the position of high sea level includes discontinuous but extensive stranded cliff lines with bases from 1 to 2 m above present high-water mark, often with associated abandoned sediments. (South Bass, Churchill Inlet, Cowes Embayment, French Island—Figs. 1, 3, 5). A number of rock platforms lying between 0·7 and 1·5 m above present platforms have been cut into the cliffs. Some have pebble and cobble gravels and sands comparable to the sediments on modern platforms. Shell material may also occur, such as at Chambers Point south of Rhyll, where *Anadara trapezia* and *Magellania* sp. are commonly included.

Present-day stranded rocky coastline features of Westernport are possibly due to the rejuvenation of earlier features developed during previous Quaternary high sea-level phases. Most of the cliffs and platforms at or above present sea level are cut into Older Volcanics. Despite their general resistance to retreat, these may be able to develop a steep profile rapidly, particularly where deep weathering or tuffaceous zones occur, as they frequently do along parts of southeastern Westernport Bay. That rapid marine cutting can occur is indicated by the remnant features, developed both at high sea level and during successive stages of late Holocene retreat (South Bass Cliff). Extensive modern platforms below the raised platforms also appear to have been cut rapidly. Cliff-lines protected from marine erosion by later Holocene deposition have been modified by mass-wasting, but others, such as those west of Rhyll, are still undergoing marine attack.

A variety of small, scattered, abandoned marine deposits (Figs. 1, 5) is associated with the abandoned cliffs behind the Cowes Embayment and Churchill Inlet. These include sandy, gravelly beach ridges of similar lithologies to the stranded ridges on the Bass Plain described below, and ribbon-like stranded sand and shelly beach deposits. Many of these are now marked by stands of *Melaleuca* sp. Abandoned salt marsh clays, etc. are found up to 0·4 m above present level, and sand ridges possibly represent old strand-lines.

(ii) *Fluvial, Inshore Marginal Sandy Zone and Other Marine Response*

Marine deposition from mid-Holocene high sea level to the present-day is marked by a variety of progressively abandoned near-shore and coastal deposits, and also by progradation of salt marsh, mangrove and tidal flats, varying according to local factors of energy, sediment supply and morphology.

The Inshore Marginal Sandy Zone showed various responses. The Bass Plain region was a low-gradient area of relatively low sediment influx with which was associated a fluvial response. In contrast, plentiful sediment supply allowed rapid deposition of a sandy substrate on shelving floors, culminating in the build-up and progradation of larger barrier, beach, and lagoon complexes. This is seen at Stockyard Point (south of Lang Lang Jetty), the Sandy Point-Middle Bank complex, and is well illustrated by the evolution of the area of the Cowes Embayment (Rhyll Swamp-The Nits-Cowes Bank).

(a) *Fluvial, and Sediment Influx Response—Bass Plain Area*

The Bass region shows both marine and fluvial response to fall of sea level: cliff-erosion and associated successively lower isolated beach ridges lying on the regressive intertidal *Sbi* sheet, and entrenchment by the Bass River into the progressively emergent part of the *Sbi* Sand sheet, and into the T_2 terrace (Figs. 3a, b).

Regression of the Inshore Marginal Sandy Zone and progradation of the Bass delta accounted for the final development of the onshore part of the *Sbi* sand sheet, the origin and characteristics of which have already been discussed. Beach ridge (R_1) with its base 1·7 m above present high-water level marks the landward limit of transgression. It overlies the oldest known beach ridge (R_0) and is followed by a succession of regressive beach ridges. In the southern part of the Bass Plain there are at least nine (R_{1-9}) narrow, relatively continuous ridges with few bifurcations. Rather than fanning from a single point, they show a striking coincidence with the succession of scalloped knicks developed in the otherwise continuous South Bass cliff-line, suggesting both rapid erosion, and the possibility of a series of still stands. In contrast beach ridges in the northern area are not as extensive, and possibly represent a coalesced sequence. The reasons for the different morphologies are not clear; possibly both orientation with respect to wind and waves, and also differences in surface gradient of the sand sheet may be factors.

Sediment forming the present-day beach ridge (R_9) is transported essentially by wave-generated longshore movement from the nearby flanking headlands and cliffs. These are areas of basalt and Tertiary sediments. The sediment is hence rich in limonitic and basaltic gravel (up to 40%). The modern *Sbi* intertidal sands contain very little gravel, which indicates a lack of off-shore sources. Shell carbonate also is a conspicuous component of the present-day beach ridges, together with a typical quartzose matrix of medium sand, admixed from the *Sbi* sand. Although texturally poorly sorted, the ridge sediments contain less than 1% material finer than sand. The older beach ridges are relatively cemented and leached of carbonate, but have the same lithology, and presumably the same genesis, as R_9.

When developed, the typical zonation associated with the modern ridges includes an offshore zone of mangroves and a landward belt of salt marsh peat and clay (Fig. 2). Peats and peaty clays are found to 1 m thick behind the present-day beach ridge, but erosion and man-made drainage changes obscure the original distribution of salt marsh. Only occasional older salt marsh remnants are found associated with the stranded ridges, the grey clay beneath ridge R_3 being an example. North of the Bass River, an extensive area of older peat lies 0·6 m above the present salt marsh level, and behind this are beach ridges which are still older.

Other entrenchment phenomena are seen in the area of the Bass River. The original physical continuity of the marine sand sheet (*Sbi*) and the T_2 terrace has been disrupted by entrenchment and lateral cutting. The main river channel has removed some of the emergent part of the *Sbi* sheet and exposed the underlying substrate. Upstream, as far as Bass, a well-developed field of large-amplitude meanders shows tidal influence. The most landward of these are at higher level and abandoned, and locally, flights of up to four distinct terraces indicate rejuvenation accompanying falling sea level (Fig. 3). The marked widening of the meander belt downstream reflects the passage from a zone of entrenchment into erosion-resistant grey clay T_1 substrate, to a zone of widespread, thicker *Sbi* sands. The extensive area of low-lying salt marsh, etc. just north of the channel developed after entrenchment.

Entrenchment into the T_2 terrace also took place in all reaches of the Bass River upstream from Bass, to a depth typically of 4-5 m, locally up to 7 m (Fig. 3; Fig. 1 shows location of section NPR). Although modern point bar deposition occurs at or just above river level, the prograding Bass delta (*Sbi*) has been the main depositional area for the influx of re-worked T_2 sediment.

(b) *Dominant Longshore Transport—Cowes Embayment*

The initial open embayment, between Cowes and Rhyll, shelved seawards backed by an erosional coastline. An earlier transgressive sand sheet may have been developed by the time of high sea level, but no evidence for this is yet available. During sea-level fall, rapid sediment supply, mainly by west-to-east longshore movement has caused progradation of about 1·2 km, building a wedge-like body of sand whose thickness increases outwards to about 20 m beneath the present shoreline. Continuation to the present-day of this eastward transport gives significance to the evolution of the complex (Figs. 5a, b).

The exact landward limit of marine conditions at the time of high sea level is unknown. Breaks in the original inner cliff-line opened landward to low-lying areas, presumably small valleys or swamps, which were subsequently closed by beach ridge systems. The isolation of the Rhyll Swamp thus was an early result of the formation of the largest of these high sea-level ridges. This ridge is a complex of gravelly sand, about 2·5 m high, broadening from 100 m to 400 m in width, and with a distinct pattern of smaller ridges fanning from a point near its eastern extremity. This pattern could be interpreted as the result of east-to-west longshore movement and therefore of energy conditions very different from those of the present. Alternatively it may simply reflect dominant onshore wave action whose refraction patterns changed as a result of progradation and progressive erosion-retreat of the headland and adjacent cliffs and platforms at the eastern end. Whichever, there is no evidence for west-to-east transport, leading to speculation that subsequent persistent eastward transport may be partly related to the opening of the Eastern Entrance at or about high sea-level time.

The major regressive sedimentation phase de-

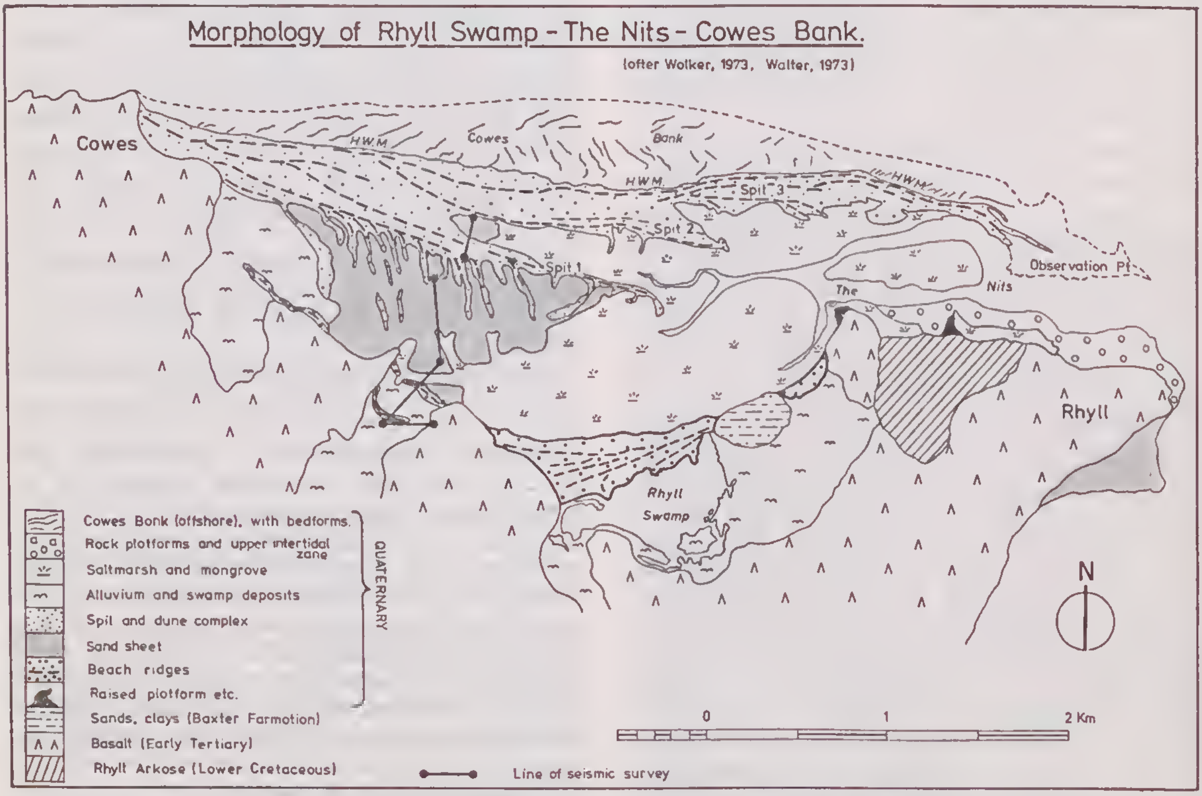

FIG. 5a—Morphology of Rhyll Swamp, The Nits, Cowes Bank.

veloped a succession of three eastward-prograded sand spits (S_1, S_2, S_3) which radiate from a headland near Cowes. A corresponding succession of tidal inlets or lagoons developed. These were probably shallow, as it seems unlikely that the spits developed as isolated features in deep water. An offshore subtidal sand sheet (analogous to the Cowes Bank lying offshore from the present-day spit, S_3) may have been the base for spit progradation, thus progressively forming the floors of the lagoons. Rapid sediment supply and construction of each of the spits occurred at or near the sea level of the particular time. Although there is a fall in elevation of 1·2 m from south to north, from the inner, oldest beach ridges to present high-water level, the exact relation of the individual spits to their contemporary sea levels, or to possible still-stands is not known. All the spits show a variety of superficial, local aeolian accumulation and deflation features.

The oldest spit (S_1) is 3·2 km long and up to 5 m high. It is notable for a number of closely-spaced, small, sub-parallel ridges developed from its inner, southern flank across the surface of the innermost part of the sand sheet. Their regularity and their high angle (about 60°) to the line of the spit cast doubt on their origin as re-curves or wave-refraction structures. The closest modern analogy, on morphology alone, may be the sand-wave bedforms on the present Cowes Bank, which are thought to be due to wave action combined with a net eastward flood-tide dominance.

Both the second (S_2) and third and largest (S_3 or Observation Point Spit), show typical re-curves. The former spit is 2·5 km long, and the latter 5 km long and up to 5 m above high-water level, but showing short-term variations at its distal end through historic time. The Observation Point Spit more or less connects and smooths the coastline between the headland at Cowes and the rocky cliffed headland west of Rhyll.

The succession of tidal inlets thus formed shows progressive mangrove, salt-marsh, and fresh-water swamp progradation, the inner, oldest area being the most advanced toward fresh-water swamp conditions prior to land-clearing. The sediments of the barrier complex are well- to very-well sorted medium quartzose sands, with relatively

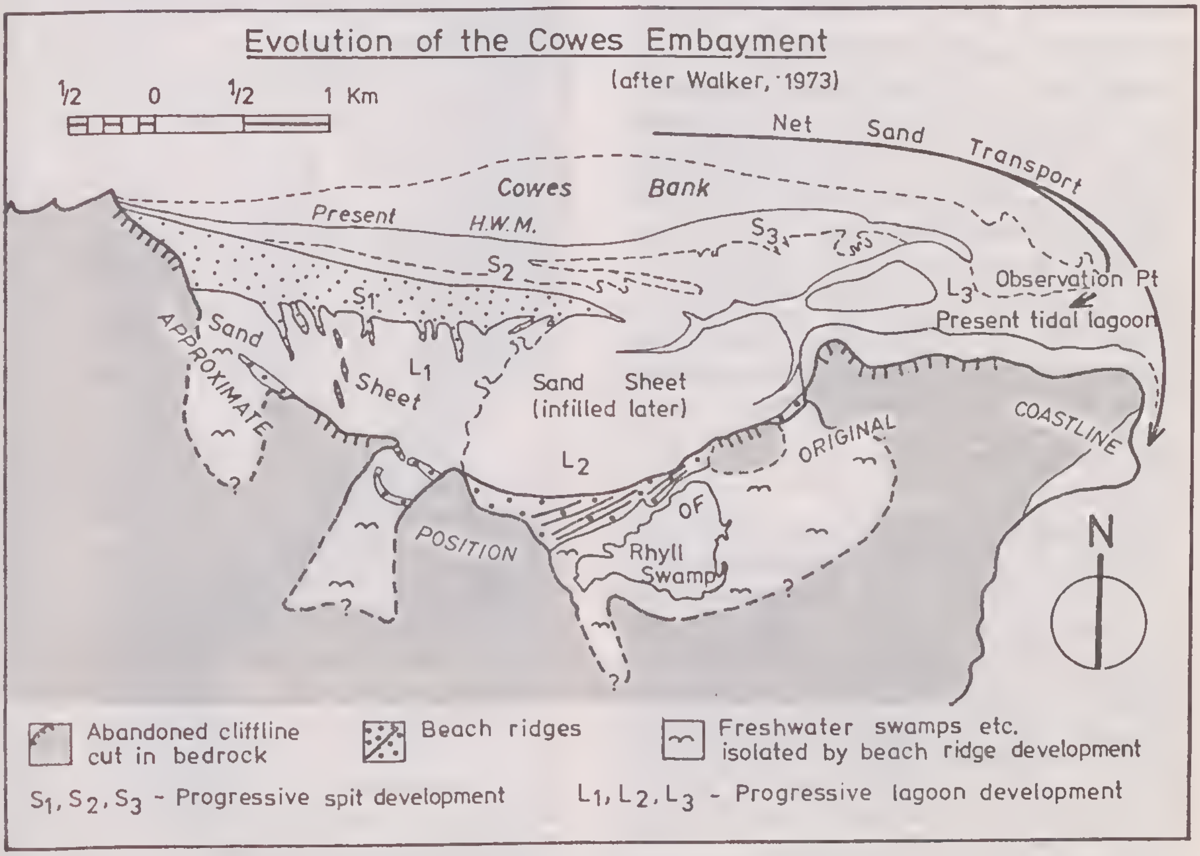

FIG. 5b—Evolution of the Cowes Embayment.

minor carbonate content. The intertidal lagoon and marsh sediments are muddier.

(c) *Intertidal Flats*

Significant net landward transport and deposition of sediment by tidal processes must have been associated with marked decline in the input of land-derived sediment to Westernport Bay. During the period of sea-level fall, progradation of swamps and salt marsh probably accentuated the physical barrier to the passage of fluvial sediment, a condition which persisted until the very recent artificial drainage and clearing of hinterland areas. In particular, the build-up and progradation of the isolated, and the embayment-head tidal flats has probably resulted from the continuation of landward transport, especially of fine-grained suspended sediment, during the regressive phase. Although essentially terrigenous, the flats contain relatively thin but extensive coquinas, either as tidal channel or wave-distributed sheet deposits. In the higher levels of the flats, these concentrations might reflect still-stands of sea level. However, the effect of sea-level change on the evolution of the intertidal areas, particularly following sea-level fall, is not known.

4C—Modern Coastal Development

Some features of the near-shore zone such as the erosion of the frontal parts of salt-marsh zones, degradation of present-day beach ridges and tidal flats, illustrated in places by re-worked shell debris, may have local causes or may reflect very recent minor fluctuations in Victoria in conditions of storminess (Bird 1973), in sea level, tidal parameters, etc. Such changes are not of the same order of magnitude as the effects of sea-level fall since mid-Holocene but also play a part in determining the morphology and sediment distribution patterns discussed below.

THE MORPHOLOGY

INTRODUCTION

The morphology of Westernport Bay is complex, and reflects the variety of processes within it. The morphological units delineate areas of the Bay which have differences in water movement, sediment transport patterns, sediment type and other processes and characteristics.

A large number of morphological units has been recognized, and individual units sharing some common characteristics have been grouped into the eight major, significantly different morphological systems of Westernport Bay, the main features of which are outlined below.

The morphological systems are often zoned, especially those in near-shore areas. The Hastings Bight Tidal Flat (*Morphological Systems*, 5, vii, Fig. 6 and Pl. 5) affords an excellent small-scale example of the characteristic zonation and distribution of most of the systems. The area shows rapid variability despite its designation as a 'tidal flat'.

Five of the systems lie essentially within the intertidal zone, the three in the high intertidal

FIG. 6—Morphology of the Hastings Bight Tidal Flat area.

zone being closely associated, namely: *Beaches, cliffs and rock platforms* which occur discontinuously, *The Salt Marsh Zone* which is fully inundated only periodically, and *The Mangrove Zone* which lies just below high-water level and is extensive, although discontinuous and relatively narrow.

The Inshore Marginal Sandy Zone forms a very persistent narrow zone around Westernport Bay, lying marginal and offshore from a variety of coastal zones and sloping very gently outwards, often to tidal flats. There are three significant modifications to this zone: (a) where longshore sediment transport dominates, (b) in inlets with uniform, low-energy conditions, (c) where land-derived sediment influxes occur.

The Intertidal Flats and Banks occupy about 35% of the area of Westernport Bay and show the greatest variability in aspect, configuration and sediment type. Three morphological types occur, as elongate flats along channel margins, as relatively small, isolated flats, and as extensive embayment-head flats. Normally their seaward margins descend steeply into channels. Areas of active overwash sand accumulation occur on and within the flats, particularly along channel margins, where they have an important stabilizing role. Shell material is often abundant.

The Offshore Banks and Shoals are relatively grass-free, as is the Inshore Marginal Sandy Zone, but are mostly subtidal. The mobile sand characteristically shows large-scale bedforms indicating significant high-energy transport.

The Embayment Plains are essentially permanently submerged. They have relatively low but irregular relief, and slope gently to their deepest margin, where they are terminated abruptly by a steep descent into a large tidal channel. The shallow inner margins are variable in character, commonly being the outer fronts of still shallower banks and tidal flats.

The Tidal Channel System comprises the minor dendritic channels of the embayment-head and isolated tidal flats, the main trunk systems of the North Arm and East Arm which lead to the dominant Western Entrance, and the more limited channel system of the Eastern Entrance. Complex flood-dominant and ebb-dominant patterns affect sediment movement, and form bars and overwash sands.

THE MORPHOLOGICAL SYSTEMS

The detailed distribution of morphological units and systems is shown in Fig. 2 and the generalized distribution of sediment types in Fig. 7. In particular the legend of Fig. 2 shows details of morphological features which are not discussed specifically in the text. Letter symbols used in the text are derived from the legend, and grid map references also refer to Fig. 2.

The geographic names proposed herein for the morphological units are provisional, but in view of the complexity of the Bay, it is necessary to have some acceptable nomenclature, which hopefully will become standardized in the future.

1. BEACHES (*B*), CLIFFS AND ROCK PLATFORMS (*R*)

2. SALT MARSH ZONE

3. MANGROVE ZONE (*M*)

These three systems have been grouped, as relatively less attention has been paid to their characteristics and sedimentation processes.

The Salt Marsh Zone lies landward of the Mangrove Zone, and is only fully inundated during high-water spring tides and storms, being characteristically cut by small meandering tidal creeks. The Mangrove Zone is usually sharply defined, lying just below high-water level. Both zones are narrow, typically less than 200 m, and discontinuous, but both have an important role in sedimentation. Mangrove Zone sediments are relatively muddy but stabilized, whereas the salt marsh characteristically has clayey sediments with some peats, which are often impure. It should be stressed that the sediment types can be quite variable, depending on local supply and energy. The dominant sediment can vary, for example from sand in the salt marsh of Watsons Inlet, to clay in the inner zones of Churchill Inlet, to areas of sediment starvation which produce salt marsh peats. Interbedded coarse grained storm and wind-blown sediment, shell debris and seagrass are found in the outer salt marsh. The balance between sedimentation and erosion is particularly delicate, especially in relation to recent variations in sea level, to erosional and constructional effects of storms, and to natural and artificial variations in vegetation density affecting sediment stability. This has been more than adequately demonstrated by the changes following removal of vegetation from various areas, for example near Warneet and in the Hastings Bight.

The Mangrove and Salt Marsh Zones are extensively developed and have easily recognizable characteristics on aerial photographs. Accordingly, they were used for map definition of 'coastline' to avoid the inconsistencies seen on a number of previous map compilations.

4. INSHORE MARGINAL SANDY ZONE (*Si* and Variants)

This is a persistent feature of the middle to high intertidal zone. It is normally a narrow (typically not more than 300 m), marginal, but not entirely continuous, relatively grass-free, sandy zone with varying proportions of mud. Bimodal combination of longshore transport and onshore-offshore (tidal and wave) sediment transport, imparts a characteristic well-defined reticulate drainage pattern, clearly visible on the aerial photographs as a textured pattern on the sediment surface. The gentle outward slope of the zone normally leads to grassed tidal flat areas, often of finer-grained sediments.

There are three distinct modifications to this otherwise relatively simple zone (i) where longshore sediment transport dominates, (ii) where its continuity is broken by inlets, in which more uniform, low energy conditions prevail, (iii) where land-derived influxes dominate as the sediment source and transport mechanism. An exceptional variation occurs in the complex Queensferry Embayment Plain, where the *Si* zone extends offshore from a point near the northern extremity of the plain (grid reference 710543), to merge with an area of overwash sand bodies (*Co, Os*) derived from the adjacent channels off the East Arm.

(i) DOMINANT LONGSHORE TRANSPORT

(a) *Cowes Bank* (*Siz*)

This is a wide, linear sandbank stretching from Cowes to Observation Point near Rhyll, and terminates in recurved spits. Most of the bank has a low gradient and is intertidal. The outer subtidal margin slopes relatively steeply to the floor of the East Arm channel. Beach sands are well sorted, whereas offshore moderately sorted medium sand occurs.

The intertidal zone of the bank shows a prominent pattern of eastward-facing sandwaves. Both the distribution of the sandwaves and their asymmetry indicate that dominant wave activity assisted by relatively weak tidal flow give rise to eastward longshore sand transport.

Tidal currents are the dominant mechanism for moving sand along the subtidal outer margin of the bank (Burrage, pers. comm.). Transport has been observed from west-to-east in the forming of migrating mega-ripples (H up to 50 cm, L = 10 to 15 m) with associated small-scale ripples. The orientation of the mega-ripple crests is somewhat oblique to the bank, so that in addition to the general west-to-east movement, there is a shoreward component which effectively nourishes the bank.

This is consistent with the prolonged eastward transport which formed The Nits. Although its terminal spit has varied in morphology within recent historic time, continuing eastward transport of sand beyond Observation Point is indicated by the offshore sands between it and the sandy cuspate beach area at Rhyll. The latter has grown considerably during this century (local resident—personal communication), and longshore intrusion of sand into the Inshore Marginal Sandy Zone of the Churchill Tidal Flats beyond Rhyll is also evident.

(b) *Lang Lang Beach:* Distinctive linear sandwaves oriented southwesterly, oblique to and just beyond the shoreline, consist of moderately sorted medium sand with a small (14%) mud content. These owe their morphology in part to north to south longshore sand movement, but are controlled by the distribution of outcrop of the Tertiary bedrock. This direction is consistent with the general longshore movement in this segment of the Bay (Fig. 1).

(ii) PRESENCE OF MAJOR INLETS (*Si*)

There are four major inlets in the Inshore Marginal Sandy Zone: firstly, the constructional Nits Inlet, and secondly, the Watsons Inlet-Blind Bight-Rutherford Inlet group, whose morphology and sediments are largely inherited. The common characteristic of the inlets is the prevalence of uniform, low-energy conditions, longshore movements being relatively weak. The reticulate drainage pattern is therefore generally lacking.

(a) *The Nits Inlet:* This has a relatively broad but very shallow entrance across the eastern extremity of the Cowes Bank, and is occupied largely by a salt marsh-mangrove complex. The Inshore Marginal Sandy Zone proper is confined to the eastern portion of the inlet, near the entrance. The sediments are sands and clayey sands with a variable clay content, and up to 30% mud. Sorting is moderate.

(b) *Watsons Inlet-Blind Bight-Rutherford Inlet:* The northwestern corner of the bay is unique in the development of a complex of inlets, which have both unusual morphology and an unusually widespread relatively high sand content. The nearby Post Office Tidal Flats are also sandy. This concentration of sand is a striking feature of the sediment distribution of Westernport Bay, and its origin, whether from hydrodynamic or other processes, is of particular significance.

The morphology of the inlets does not resemble a drowned fluviatile drainage system. Watsons Inlet and Blind Bight are broad, flat and shallow depressions, as is the isolated area of salt marsh above high-water mark at the head of Cannons Creek. Their interpretation as drowned but somewhat modified, irregular topographic depressions between northwest-trending aeolian dune ridges of the Pleistocene Cranbourne Sand is supported by their position within the main sand belt.

In Watsons Inlet and Blind Bight, and in the grassed depression near Rolfe's Marina, the channels are sometimes interconnected in unusual arcuate to intersecting patterns within the very broad and flat areas of the Inshore Marginal Sandy Zone. Compared with channels of other morphological units (especially the tidal flats), they have greater variation in width and depth, and have very poorly defined edges. These features reflect a substrate dominantly of poorly-grassed sand, in a low-energy environment. In Watsons Inlet, small but relatively high-energy tidal creeks emerge from the mangrove zone into broader channels where they deposit sand as small bars.

Rutherford Inlet (and China Bay to the east) contrasts with the other two inlets in having a long, narrow and straight northerly trend. At Warneet, this changes abruptly to northeasterly where the tidal reach of Cannons Creek cuts through a prominent higher ridge of Cranbourne Sand, upstream of which another broad isolated depression occurs, this time occupied by salt marsh. Morphological control by original topography of the Cranbourne Sand is at least partly responsible for this pattern. The distribution of the Inshore Marginal Sandy Zone is correspondingly restricted, diminishing rapidly in the narrow tidal Cannons Creek.

The dominance of sand in this part of Westernport Bay is correlated with relic Cranbourne Sand, especially as there is no evidence of marine hydrodynamic processes concentrating sand to such a degree. Low availability of mud is illustrated by the unusual sandy salt marsh deposits in Watsons Inlet—an area where mud could normally be expected.

Formation of the inlets by marine erosion is discounted, because of the similarity of their morphology with that of the isolated salt marsh area at the head of Cannons Creek, and the evidence for general progradation rather than erosion in this segment of the Bay.

(iii) Influx Areas (*Sif* and Variants)

A feature of Westernport Bay is the relative lack of direct natural drainage, the Bass River being the only significant natural input. Clearing of the heavily forested drainage basin has probably resulted in changes in discharge, and at least some dynamic and sedimentation response in the Bass Delta area. Other natural input streams drain relatively very small areas with no great relief, and their sedimentation effects are local.

Artificial straightening and opening of the Lang Lang River, the Bunyip River and its associated drain system and of other smaller drains is also noticeably modifying the Inshore Marginal Sandy Zone. Draining of the Koo-wee-rup Swamp has initiated rapid high-energy transport of significantly increased loads of coarser material, beyond the previous sedimentation barriers in the undrained swamp. In some cases, active headward erosion is associated: for example, on the Lang Lang River where the knick point, 4·5 m high, has retreated approximately 12 km since 1909 by erosion of the Heath Hill Silt. Headward movement of up to 100 m in one day has been recorded (B. R. Thompson, pers comm.).

(a) *Bass Delta:* The delta-like form of the Bass River mouth results from a combination of river discharge and the processes of the Inshore Marginal Sandy Zone. North to northwesterly and southwesterly winds create relatively high energy conditions, a further factor in developing the marked contrast between the sandy sediments of the Bass influx and those of more-protected nearby morphological units.

The Bass Delta fringes the East Arm Embayment Plain, and is a thin sheet prograding outwards over the older Quaternary.

Sedimentation at the Bass River mouth is indicated by levees flanking the relatively stabilized main distributary channel, and by the general morphology. The close similarity of the size characteristics and composition of the sediment of the youngest river terrace (T_2) and of the delta sands also indicates that the Bass River is the sediment source.

Two sediment zones are recognized: the Inner Sandy Zone (*Sbi*) of well-sorted sand, bounded by the Outer Muddy Zone (*Sbo*) of poorly sorted, clayey very fine sand. There is no sharp demarcation between these. Their upper surfaces are continuous and slope seaward at approximately the same gradient. The front of the outer zone slopes more steeply to the East Arm Embayment Plain, where only finer sediments are found, emphasizing the local dominance of the Bass River as the sediment source.

(b) *Lang Lang River:* Influx from the Lang Lang River from its major, and other minor distributaries, is also forming a small thin sand sheet, whose frontal slope however is not as marked as that of the Bass Delta. North to south transport is indicated by the general asymmetry of the sheet, and by the lack of a prominent Inshore Marginal Sandy Zone to the north. Lower energy conditions are further indicated by the occurrence of poorly sorted medium sand with a mud content of 20%.

(c) *Bunyip River (and 'Main Drain'):* Rapid sedimentation of a fan-like sand sheet is indicated by anastomosing distributary patterns of major and minor braided channels radiating from the drain mouths, which contrast strongly with the Bass Delta (and Lang Lang River). These distributaries continue further seaward than the normal outer limit of the Inshore Marginal Sandy Zone on either side and are less stabilized than those of the Bass River. Periodic large-volume, high-velocity discharge of the drains reduces the significance of tidal and wave processes, and the sediments, mainly pebbly coarse sands, also differ from those of the Bass Delta. They also contrast strongly with the Tooradin Tidal Flat sediments, over which they are prograding.

5. Intertidal Flats and Banks (T and Variants)

The Intertidal Flats and Banks as delineated are largely, but not entirely, exposed at low tide: the sloping seaward margins are only rarely exposed. The flats are characteristically grassed to a varying degree, and their drainage channel patterns are mainly dendritic. Generally the sediments are muddy, with some notable sandy exceptions. Sand bodies (*Co, Os*) found on the outer margins (and within) otherwise muddy flats, owe their origin to transport on to the flats, in particular by overwash from channels. Shelly material may be an important constituent, either as discrete shell coquinas within the tidal flats or as surface lag concentrations. The latter are partly re-worked and partly from present-day organisms, and often armour the overwash sand bodies.

Three distinct morphological types have been recognized, varying in aspect, configuration and sediment type:

(a) elongate channel-margin flats and banks (Tyabb Tidal Flat and Bank, Fairhaven Bank) often characteristically cut by large linear channels, especially in their more offshore areas (Middle Spit Tidal Flats, Peck Point Tidal Flats, Freeman Point Banks).

(b) relatively small, isolated flats with dendritic to meandering tidal channels (Hastings Bight, Hanns Inlet, Churchill, and Corinella Tidal Flats). These owe their existence and individual characteristics largely to pre-existing substrate morphology and sheltered aspect.

(c) extensive embayment-head flats (Tooradin and Post Office Tidal Flats) with dominantly dendritic channel patterns. The tidal range for the Bay increases inwards from about 1·2 m, and these flats are associated with the maximum range of up to 3·3 m during spring tides.

Sedimentation and progradation of all three types has been largely by landward sediment movement. There is a general lack of major sources of land-derived sediment, and additional evidence for landward transport is seen in the generally fining-inward sediment distribution (until the Inshore Marginal Sandy Zone is reached), and also in compositional data, such as shown by the Churchill Tidal Flats.

(i) *Tyabb Tidal Flats and Banks:* This is the marginal but narrow unit running northwards from Long Island to Quail Island, and enlarging where it extends into the entrance of Watsons Inlet.

The Long Island-Watsons Inlet segment forms a grassed, shelving margin on the west side of the North Arm Channel, lying seaward of the Inshore Marginal Sandy Zone, having occasional overwash sands (*Co*). In marked contrast, in the east-west segment south of Quail Island overwash sands are prominent, and are accumulating on banks which are steeper and higher. These are derived in part by eastward transport of the effluent sediment (*Cb*) from the inlets on to the margins of the flats by flood-dominant currents (see *Morphological Systems* 8, iv). A similar transport pattern is present in the vicinity of the entrance to Rutherford Inlet.

Sediment of sand-silt-clay composition is found only rarely in Westernport Bay, but occurs both off Scrub Point and south of Quail Island (localities 450, 453).

(ii) *Middle Spit Tidal Flats and Fairhaven Bank:* The offshore lens-shaped Middle Spit Tidal Flat is dissected by relatively linear channels, the main one being the Middle Spit Channel. The term 'spit' is inappropriate in a morphological sense. This is the dominant unit marginal to the North Arm Channel. Although its progradation history is not yet known in detail, there are indications that this may have occurred relatively rapidly. It obviously plays an important part in the water circulation patterns of the North Arm.

The main sediment type of the flats is clayey silt, sand being added from prominent overwash mobile sandwave systems (*Co*), particularly on the westernmost margin but also flanking the Middle Spit Channel. Towards the northern end of this channel some grassed sandwave systems (*Cog*) may be older and non-active, as their oblique orientation suggests formation by flood-dominant transport. At present, the bank and shoal morphology suggests bedload ebb-dominance for much of this unit, particularly illustrated by the distribution of the grass-free Offshore Banks (*Od*) along Middle Spit Channel, and elsewhere.

Along the Fairhaven Bank north from Tankerton, the channel edges are relatively poorly defined because of grassed areas, lying at greater depths than normal, along their margins.

(iii) *Peck Point Tidal Flats:* The morphology is dominated by the linear Blakes Channel, opening at both ends into the East Arm trunk channel, and dividing the area into an inner and outer flat. Tidal circulation patterns are important in the development of the outer flat, but proximity to the outcrops of Tortoise Head and the arcuate, backing cliff-line suggest that overall the flat may owe its morphology to the older bedrock.

Clayey silts and sandy clays are accumulating on the more sheltered inner flats on the shoreward side of Blakes Channel, whereas the outer flat is more variable. The central part of the outer flat is relatively fine-grained, of sandy clay, and largely grassed. The marginal zones are typically coarser, particularly on the outermost margin facing the East Arm Channel where a large overwash area (*Co*) of sands and clayey sands grades outwards to sands in the offshore shelving marginal banks (*Odg*) along the channel, and south of Tortoise Head. The margin of the outer flat, along Blakes Channel, has a greater content of fine sediment, clayey or silty sands. Shell layers and shell lag deposits on the flats reflect both supply from nearby sources and re-working of older shell beds (*Te*).

The distribution of these sand bodies (*Co, Odg*), together with bedform orientations, indicate net transport of sand towards the northwest on to the outer flat and across its western shelving margin by dominant ebb-tide movement. Onshore sediment movement occurs also by wave action. The moulding of the offshore bank (*Odg*) southwest of Tortoise Head is clearly dominated by ebb-flow, leading into the head of the Western Entrance Channel.

(iv) *Freeman Point Banks:* This is a system of elongate, somewhat irregular overwash sand bodies (*Co*) with associated elongate offshore banks (*Od*) formed in response to strong flood-tide transport from southwest to northeast. Sand mobility is shown by the pronounced bedforms. These are predominantly flood-oriented, though some indicate modification by lesser ebb-tide transport. Flood movement occurs up a series of blind channels behind the bank system, and water then over-spills across the banks back into the main East Arm Channel. The banks are basically stabilized by grass, but rapid sand movement may alternately cover and uncover the grassed areas. The sand is similar to the channel population in having a mean size of medium sand, with less than 10% mud. This unit extends from Stockyard Point on French Island, northwards beyond Sandy Point to include the flood-tide overwash sands (*Co*) on the southern extremity of the Tooradin Tidal Flats south of Bluff Point (see *Morphological Systems* 8, iv).

The Freeman Point Banks contrast strongly with the intertidal flat areas in being a zone of high-energy sand transport, but are included in this morphological system because of their position in the intertidal zone, and their grass cover.

(v) *Churchill Tidal Flats:* Named after Churchill Island, these occupy Churchill Inlet, from Newhaven to Rhyll, and for most part are sheltered, especially from southerly and westerly wind-generated waves. It is therefore a low-energy environment, reflected by total dominance of clay-size material within the flats, except near the channels and along the Inshore Marginal Sandy Zone. Landward sediment transport, probably by dominant flood tides up the tidal channels, is shown by the high percentage of quartz in the clay-size fraction, since no hinterland sources of quartz exist. The balance between accumulation and erosion of the clayey sediments varies locally. In some internal areas, and along the front margin of the flats, erosion occurs by the flow of ebb-tide water directly over the edge of the flats, or through minor tidal creeks. The lack of stabilizing overwash sands on the tidal margin reflects the lack of sand transport in the East Arm Embayment Plain area.

The prominent Inshore Marginal Sandy Zone is mainly the result of longshore movement, with possibly a contribution from up-channel bedload transport. Intrusion of sand occurs from the Cowes Bank into this zone.

In the outer margin of the Churchill Tidal Flats (and in the sub-parallel offshore zone) the sediment varies from a silty clay (Rhyll to Churchill Island) to coarser sandy clays (Churchill Island to Newhaven). This differentiation probably reflects interaction between tidal movements from the main Western Entrance up the East Arm, and from the Eastern Entrance, flood tides from the latter causing some northwestward incursion of sand. Entrances of some of the minor tidal flat channels near the Eastern Entrance are deflected by this net northwestward movement. Sediments still further offshore are also sandy (Locality 486—31% sand), and in the absence of an offshore sand source (shown for example by Locality 487 where silt with only 6% sand is found) a northwestward transport zone running approximately parallel to the front of the flats is indicated.

(vi) *Corinella Tidal Flats:* These are morphologically similar to the Churchill Tidal Flats. The meandering channels include clayey sands whereas the tidal flats contain silty clays. At the southwest extremity of the flats, flood transport is locally dominant and brings sand (*Os*) from the main East Arm Channel on to the flat. This forms an irregular sheet, with reticulate drainage patterns similar to the Inshore Marginal Sandy Zone. The unit as a whole is relatively protected from strong flood tides by Schnapper Rock and Pelican Island, but is an important path for lower energy ebb-tide flow, including water from parts of the Queensferry Embayment Plain.

(vii) *Hastings Bight Tidal Flats:* This is a small, complex inlet, closest in morphology and degree of protection to the Churchill Tidal Flats, and strongly contrasting with the Middle Spit Tidal Flats on the opposite side of the North Arm Channel. The fine-grained sediments of the tidal flat (*Tg*) lie seaward of the well-zoned systems of Salt Marsh, Mangrove (*M*), and the Inshore Marginal Sandy Zone (*Si*), the areal distribution of the latter being increased by the protrusion of the bedrock Sandstone Island. Sand reappears in the outer part of the flat, seen in overwash sands (*Co*) and marginal (*Odg*), and intertidal (*Os*) Offshore Banks.

(viii) *Hanns Inlet Tidal Flats:* In contrast to other isolated tidal flats, the inner part of this flat is unusually sandy; the dominant source of this sand is probably the nearby Sandy Point. Modifications by man complicate the interpretation. In contrast to the inner sandy area, an outer muddy area (Locality 443—100% mud) extends northwards from the inlet possibly to the unnamed Crib Point flat of similar muddy character, and also southwards nearly to Sandy Point. Shell material is an important component here also, especially as shell coquinas, underlying the flat, and exposed along the margin of the North Arm trunk channel.

(ix) *Tooradin Tidal Flats:* The large embayment-head tidal flat area has a morphological continuity, and includes the Post Office Tidal Flats and the Tooradin Tidal Flats. Two morphological sub-units are recognized in the latter, the main one lying north of the trunk channel and extending from Rutherford Inlet eastwards to the main tidal divide of the Bay. Its southern boundary is defined approximately by a line along Boulton Channel, swinging towards Palmer Point. The second, smaller but complex sub-unit lies south of the tidal divide, extending towards the Stockyard Point-Sandy Point constriction, and has straight rather than meandering tidal channels.

In the westernmost part of the Tooradin Tidal Flats sand is present, expressed in the sandy Offshore Banks and Shoals (*Os*) which are essentially part of the Barrallier Island Banks. The sand content diminishes rapidly eastward, and an essentially sand-free zone grading to clay-dominant sediment has been approximately delineated in the eastern part (Fig. 7). The channel margins are also sandy, due to flood-tide overwash transport (*Co*). Irregular overwash sheets on the divide between the Boulton and Bouchier Channels show flood-oriented bedforms.

Although mostly grassed, some parts of the flats are bare, but appear to be stable, probably because of mud cohesion. Similar cohesion possibly accounts also for lack of evidence of rapid lateral migration of the lesser channels.

(x) *Post Office Tidal Flats:* These occupy the area south of the main channel and Boulton Channel, extending eastward from Scrub Point as far as Palmer Point. The striking, somewhat elongated depression of the 'Post Office' lies centrally. Its origin is not certain.

These flats contrast sharply with the Tooradin Tidal Flats: they are generally sandy, with moderate to good sorting throughout, and have an even greater development of associated sandy Offshore Banks and Shoals. The margins of the channels are relatively diffuse and difficult to define on aerial photographs. This indicates grassed, relatively gently-sloping channel walls, contrasting with the steeper (vertical or near-vertical) channel walls of the Tooradin Tidal Flats, and suggests lower stability of the sandier sediments of the Post Office Tidal Flats.

6. OFFSHORE BANKS AND SHOALS (*Oc, Os* and Variants)

These also are relatively grass-free but mostly sub-tidal (*Oc, Od* and variants), with the exception of the Barrallier Island Banks, the Palmer Point Bank and other unnamed areas which are in the intertidal zone (*Os*). The latter are included here because they are slightly higher than the surrounding grassed tidal flats and associated overwash (*Co*) areas.

(i) *Intra-channel Shoals:* These are relatively small sand bodies with various origins, occasionally underpinned by bedrock. They include Joes Island, Eagle Rock and Crawfish Rock in the north; shoals off Corinella; shoals on the west side of Middle Spit, and shoals in the Middle Spit Channel. In the latter they indicate ebb-transport.

(ii) *Middle Bank:* This extends southwesterly from Sandy Point, with its western margin defined approximately by the 6 m bathymetric contour. This is a high-energy area where medium and coarse sands form a variety of sand waves and other bedforms, the orientation and asymmetry of which offshore from Somers and Sandy Point indicate dominant west-to-east flood-tide transport, with modification by lesser ebb-tide transport near the main channel. This pattern is probably part of an overall net flood-dominance across Middle Bank with movement patterns broadly paralleling the arcuate Flinders-Sandy Point shoreline. Wave and breaker activity is frequent.

(iii) *San Remo Bank and The Narrows Tidal Delta:* Following late development of the Eastern Entrance Channel and truncation of the Churchill Tidal Flat, inward sand transport has subsequently built a small flood-delta (*Cb*) inside The Narrows. Sand transport also seems to occur in a northwest direction along the frontal zone of the Churchill Tidal Flats, but does not appear to encroach far into the East Arm Embayment Plain.

On the San Remo Bank, outside The Narrows, bedforms indicate dominant ebb movement along the western channel of the entrance, with wave and flood transport across the eastern part of the bank. The origin and transport directions of the sand are unknown: the Cape Woolamai sand dune complex may be one local source.

(iv) *Barrallier Island Banks:* This is an inclusive term for banks in the general vicinity of Barrallier Island. They include Barrallier Island itself, and banks east of Chicory Lane Channel; banks offshore from Adams Point; and banks flanking each side of the entrance of Gentle Annie Channel. Their abundance here is associated with sand of probable relic origin. They form smooth, flat intertidal sand areas, and are surrounded by a peripheral zone of textured sand, morphologically equivalent to the Inshore Marginal Sandy Zone. Associated unusual curvilinear, north-south trending ridges are essentially composed of moderately sorted mud-free medium sand, with slight positive skew (grid reference 544617).

(v) *Palmer Point Banks:* The Palmer Point Banks lie within the sandy Post Office Tidal Flats as irregularly-shaped, flat sand banks. The sediments are moderately sorted fine sands with a significant mud content (17%—Locality 428). Their occurrence is again suggestive of relatively short-distance transport of relic sediment but in a low energy environment, where admixing of introduced mud may occur.

7. Embayment Plains

Three submerged embayment plains have been delineated (Fig. 1). These are relatively flat areas with only minor, but often irregular, relief (rarely greater than 2 m). They exhibit a basin-like morphology in that they are partially ringed on their inner margins by depositional complexes of tidal flats and banks. The latter are commonly being built with a relative steep front outwards from the shoreline into the deeper water of the embayment plain.

The embayment plains slope gently outwards, until terminated, often abruptly, by a steep descent to a major trunk tidal channel. The relatively flat but gentle slope may be an essentially inherited Quaternary feature, and the ultimate positions of the outer margins and the trunk tidal channels may have been determined by entrenchment during low sea level. Their irregular relief is probably due both to erosion, and to present-day construction by sediment transport. The basin-like morphology may be accentuated by an outer rim, as in the submerged East Arm Bank along the outer margin of the East Arm Embayment Plain.

(i) *The Western Entrance Embayment Plain* slopes gently southward. Its depth increases from about 4 or 5 m at its northern margin, to about 18 m at the Western Entrance, sloping fairly uniformly with gradients of up to 1:1000 (approximately). The embayment plain is flanked on its west and north margins by beach, rock platform and Inshore Marginal Sandy Zones of the Mornington Peninsula, and its eastern flank is formed by the shallow Middle Bank. In the shallow zone offshore from Somers, irregular but patterned areas of seagrass occur, their distribution partly controlled by rock outcrops, some of which are cemented and biologically-bound sands. Medium to coarse sand occupies the area of the plain to about the 18m bathymetric contour, beyond which the sediment cover appears to become sparser rapidly.

(ii) *The East Arm Embayment Plain* is close to horizontal in its central portion where it lies at a depth of about 4 m. Its shallower boundaries are formed by the Churchill Tidal Flats, The Narrows Tidal Delta and the Inshore Marginal Sandy Zone from San Remo to the Bass Delta and between Reef Island and Corinella. In the latter area rock platforms are found more extensively.

The embayment plain is truncated on its outer edge by the main East Arm Channel, along which the submerged East Arm Bank extends from Corinella southwesterly towards a point north of Rhyll. This forms a distinct, higher outer rim to the embayment plain. Its crest, ranging from 2 to 8 m in height above the level of the plain, and its eastern flank descending to the plain, consist of medium sand, with some admixture of mud in places. Dominant sand transport from the main East Arm Channel appears to have built the bank by a sub-aqueous overwash mechanism. This is ascribed to flood-tide transport (Fig. 1), but ebb transport may also concentrate sand on the bank and possibly moulds its western extremity.

Despite this and other peripheral sand sources, the East Arm Embayment Plain is strikingly isolated. Inward transport of sand is minimal.

The embayment plain shows a coarse-to-fine gradient towards the deeper water, where silt and clayey sediments occupy the central and eastern portions. The only sand-size material is biogenic carbonate. Further, the mud percentages, although variable, increase toward the centre of the embayment plain where sorting values trend to poor and very poor. The association of finer sediments with deeper water is relatively unusual in Westernport Bay where, in general, the deeper parts are high-energy tidal channels.

(iii) *The Queensferry Embayment Plain* is both small and complex and differs significantly from the other two embayment plains. In particular, it is shallower and grades into the intertidal areas without any perceptable break. The Inshore Marginal Sandy Zone also shows exceptional features.

On the western boundary of the embayment plain the main East Arm trunk channel bifurcates and linear channel-derived sand bodies (*Co* and *Os*) are accumulating on the banks of both branches. Complex, somewhat anti-clockwise circulation patterns are suggested by the bank morphology and inconsistent bedform orientations. Fine clay-rich sediment, with only small admixtures of sand and silt, predominates in the embayment plain.

8. The Tidal Channel System

Tidal energy supplies the drive for most sediment movement in Westernport Bay, with the tidal channels the main system for transport of bedload and probably also of suspended load. Relatively high tidal velocities have resulted in the overall concentration of sand in the channel bedload (Fig. 7), even in the relatively minor channels within the embayment-head tidal flats. In contrast, finer sediment is generally concentrated in marginal, shallower, lower-energy units. The overall fining-landward sediment distribution expresses the very minor role of streams, both as flushing agents and in contributing land-derived sediment to the Bay. Characteristic estuarine circulation and sediment movement patterns, driven by salinity gradients induced by fresh-water input, are also probably minimal in the channels, where rapid mixing has been reported (Hinwood 1969, 1972). Wind-generated waves affect sediment movement in the outer part of the Western Entrance and locally in shallower areas.

Westernport is therefore essentially a tidal embayment dominated by its elongate, linear trunk channels (North Arm, East Arm, West Entrance Channels). The Eastern Entrance Channel system contributes only about 15% of the water entering in any tidal cycle (Hinwood 1969) but is of significance to the circulation of the adjacent part of the Bay.

Opposite margins of the trunk channels often show very different morphological characteristics. Marked cross-sectional asymmetry is a striking feature, for example, of the Western Entrance Channel, of the North Arm Channel (from Hastings to French Island) and of cross-sections along the East Arm. This asymmetric distribution must arise through marked differences between the paths of dominant flood-tide and ebb-tide movements, and also probably in their velocity characteristics. The general distribution of the morphological units, and their internal characteristics allows the development of the tentative broad outline of sediment movement patterns shown in Fig. 1.

In the major channels, water depth limits interpretation of the floor, but in places a variety of linear channel bars and other features formed by bedload material can be distinguished. The channel substrates are predominantly of potentially mobile quartzose and biogenic carbonate sand, but are variable and include muddy sands, coarse lag gravels, biologically-bound substrates, and areas of bedrock outcrop.

Numerous, ribbon-like suspended sediment concentrations are prominent in, and elongated parallel to, the length of the channels. They are discernible on aerial photographs (Pl. 6), and are not to be confused with bedload structures, visible in shallower water. The individual streams of suspended sediment have sharp boundaries, some originating from individual source areas, such as the larger tidal flat channels feeding into the trunk channels. Although rapid mixing has been reported (Hinwood 1969, 1972), some of these discrete water masses show a surprising degree of down-channel persistence, for example from the North Arm and East Arm Channels, extending across Middle Bank and also well into the Western Entrance Channel past McHaffies (Pl. 6). Their pattern presumably marks ebb-tide flow. This has implications for the question of sediment-water mixing, especially lateral mixing in the Bay, and for example, for the dispersal paths of fine-grained suspended spoils in the channel system.

(i) *North Arm Trunk Channel:* The channel position and morphology is broadly controlled by bedrock outcrops on the mainland and French Island, a striking exception being the relatively small Middle Spit Channel which at present shows ebb-dominance.

Sediment distribution varies from south to north. Near the Tortoise Head constriction, the sediment is very coarse sand and gravel, poorly sorted (negative skew suggesting lag sediment), but northward it decreases in mean grain size in

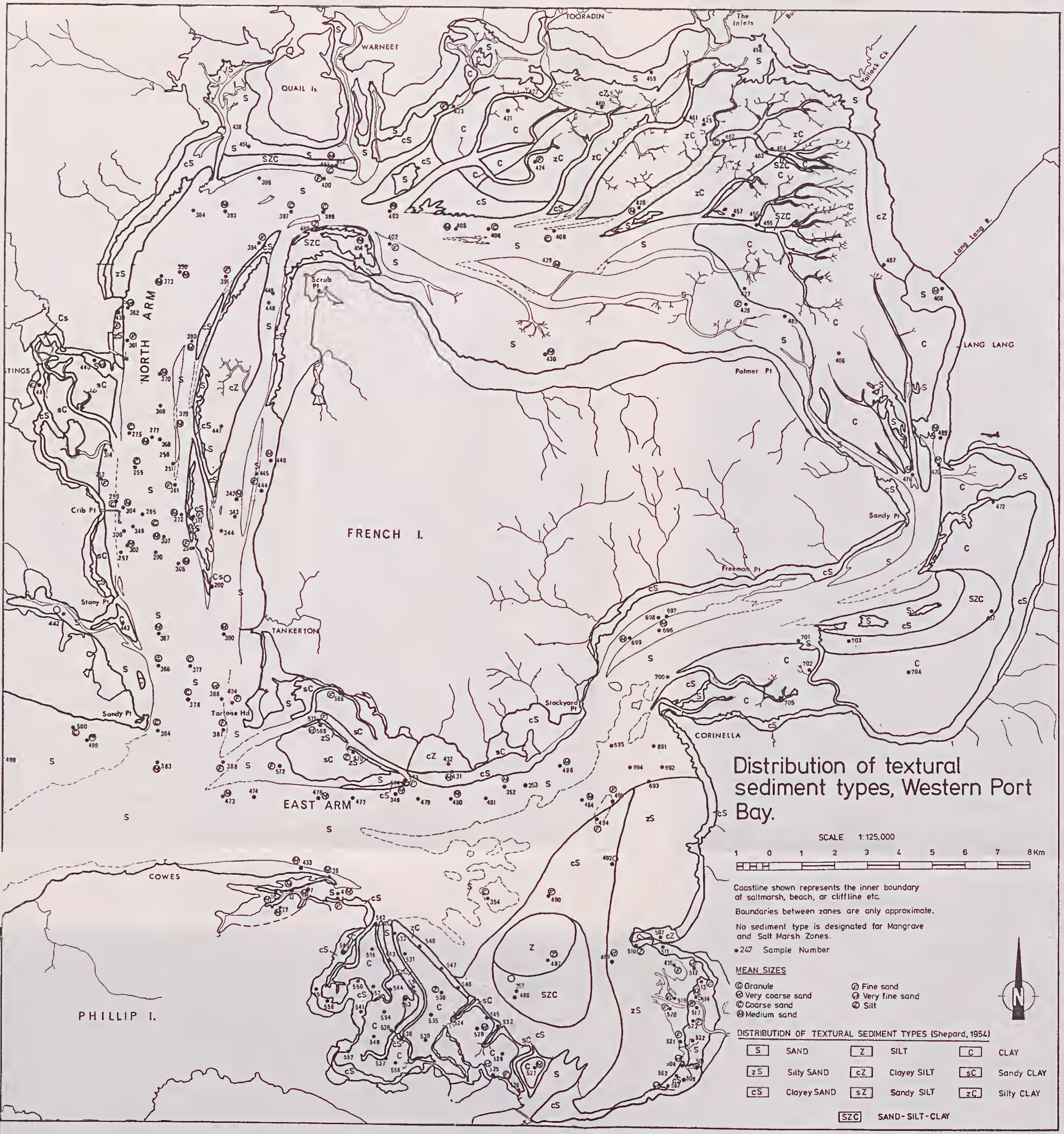

Fig. 7—Distribution of textural sediment types, Westernport Bay.

Proc. R. Soc. Vict. Vol. 87, Art. 11, Marsden and Mallett, Fig. 7.

irregular fashion to coarse sand off Crib Point, then to fine sand until Crawfish Rock, where the sediment reverts to coarse sand again. This distribution is probably related to the bathymetry of the channel, which shallows northward to the vicinity of Crawfish Rock, where it rapidly deepens.

(ii) *East Arm Trunk Channel:* Conditions of transport and supply differ from the North Arm, and medium sand is distributed relatively uniformly throughout the channel. The occurrence of only moderate sorting is due to coarse biogenic carbonate, an important constituent which includes large proportions of brachiopod and molluscan debris. The marginal overwash deposits on the Peck Point Tidal Flats also contain similar debris.

(iii) *Western Entrance Channel:* This is confined between the largely rocky northern margin of Phillip Island and the seaward margins of Middle Bank and the Western Entrance Embayment Plain. Virtually none of the confines which fix the position of the actual entrance are formed by sediment deposition.

It is obviously a high-energy channel, with coarse to very coarse sand, some pebbly, with at least the coarser pebble fraction a lag deposit and not part of the mobile bedload. Core sampling on the higher areas within the Western Entrance during the Westernport Seabed Investigation, although not designed to give bedload sediment samples, indicates the presence of pebbly sandy gravels (Barton 1974). These may be the source in part of the bedload pebbly material.

The Western Entrance is affected by strong tidal and wave action, and has, in parts, only sparse sediment cover. Further offshore the striking Flinders Bank represents a substantial sand-constructed feature whose morphology may relate in part to inward and eastward longshore movement. The inner zone of Bass Strait has a relatively smooth floor with quartzose sands passing out into finer quartz-carbonate sands. Areas of blue-grey to green muds appear to be confined to depths greater than 75 m (Holdgate 1973, Davies & Marshall 1973).

(iv) *Minor Tidal Channels and Creeks:* In the North Arm, dendritic channel patterns become more prominent eastward towards the main tidal divide. The meanders generally have low sinuosity, and anastomosing patterns are rare, with the exception of the headwaters of Bouchier Channel and in Watsons Inlet and Blind Bight. Individual channels of the system also have different sedimentation roles, with differences in ebb-tide and flood-tide behaviour suggested by morphology and sediment characteristics (particularly mean grain size and sorting).

Sediment of relatively coarser mean grain size, but poorer sorting and higher mud percentage in the Bunyip River-Lyall Channel system, and in the Yallock Creek-Bouchier Channel system, shows that these two systems carry much of the land-derived sediment influx from the north, with the first dominant. Improvement in sorting values in Bouchier Channel results from down-channel winnowing.

This role is confirmed by the presence of considerable suspended sediment in these channels, and ebb-flow sediment transport (assisted by stream discharge) is further suggested by the linear channel bars (*Cb*) at their junctions with the major trunk channel. Grassed overwash sand bodies (*Cog*) on the western bank of Lyall Channel are inactive and have an uncertain but possibly related origin.

Net down-channel transport of sand (*Cb*) in Horseshoe Channel, Inside Channel, and Chicory Lane Channel occurs. However, evidence for ebb-movement for Boulton Channel is notably lacking, indicating some degree of flood-tide transport forming overwash sands (*Co*).

Other intertidal areas with dendritic channel systems include the five isolated tidal flat units. The Watsons Inlet channel system (and Blind Bight), however, show different characteristics, with a weakly reticulate, more irregular channel pattern, and the channels themselves broader and shallower than in other intertidal areas. As a result of ebb-flow in the channels from Watsons Inlet and Rutherford Inlet, small sand bodies (*Cb*) are formed at their confluences with the main trunk channel. These are then subjected to flood-tide movement, modifying the shape of the *Cb* sand bodies and transporting sand up the North Arm Channel and on to the adjacent bank areas, with general northeastward movement forming overwash bodies (*Co*).

In the East Arm, the minor channels immediately south of the tidal divide contrast strongly in morphology with the dendritic system to the north, in that they are relatively long and straight. Differentiation of ebb- and flood-tide circulation patterns is clear in the channel system between Stockyard Point and Sandy Point. Large washover sand fields (*Co*) associated with the easternmost channel are a response to net flood transport and in the western channel ebb-dominance is indicated by the presence of sand bars, etc. (*Cb* and *Od*). The flood-dominant channels within the Freeman Point Banks trend generally southwest to northeast arranged *en echelon* between the individual banks and the Inshore Marginal Sandy Zone.

SEDIMENT DISTRIBUTION

Size analysis data and statistical parameters have been obtained to assess their applicability, firstly, in the recognition of sedimentation provinces (morphological units and regional provinces, e.g. major areas of sand or mud dominance), and secondly to interpret sediment sources and processes. In the light of the complexity of the sedimentation patterns already described, knowledge of sediment distribution and movement in the Bay must be regarded as incomplete.

CHARACTERISTICS OF SEDIMENT TYPES

Grain Size

Mean grain sizes were calculated using the sand and silt fractions only (recalculated to 100%) and were then grouped into classes of the Wentworth Scale. Mean grain size class names should not be confused with the nomenclature of sediment types based on sand-silt-clay ratios (Figs. 7, 9). Clay fraction data (and therefore clay-dominant sediments) were omitted from the mean size calculations because of the complexity of the mechanisms of transport and incorporation of clay into the sediments. The mean grain sizes therefore are more meaningful for the bedload population and particularly for channels. Nearly 60% of the samples had less than 10% clay. Data taking into account the full sediment range in the samples is expressed as mud percentage (Fig. 8), and in the distribution of the sediment types based on sand-silt-clay ratios.

Sediments having mean grain sizes of silt, fine and very fine sand (Table 2) are largely accounted for by the Tooradin (and other) Tidal Flats, and also the region including the East Arm Embayment Plain. In the major trunk channels (North Arm and East Arm) mean sizes of coarse and

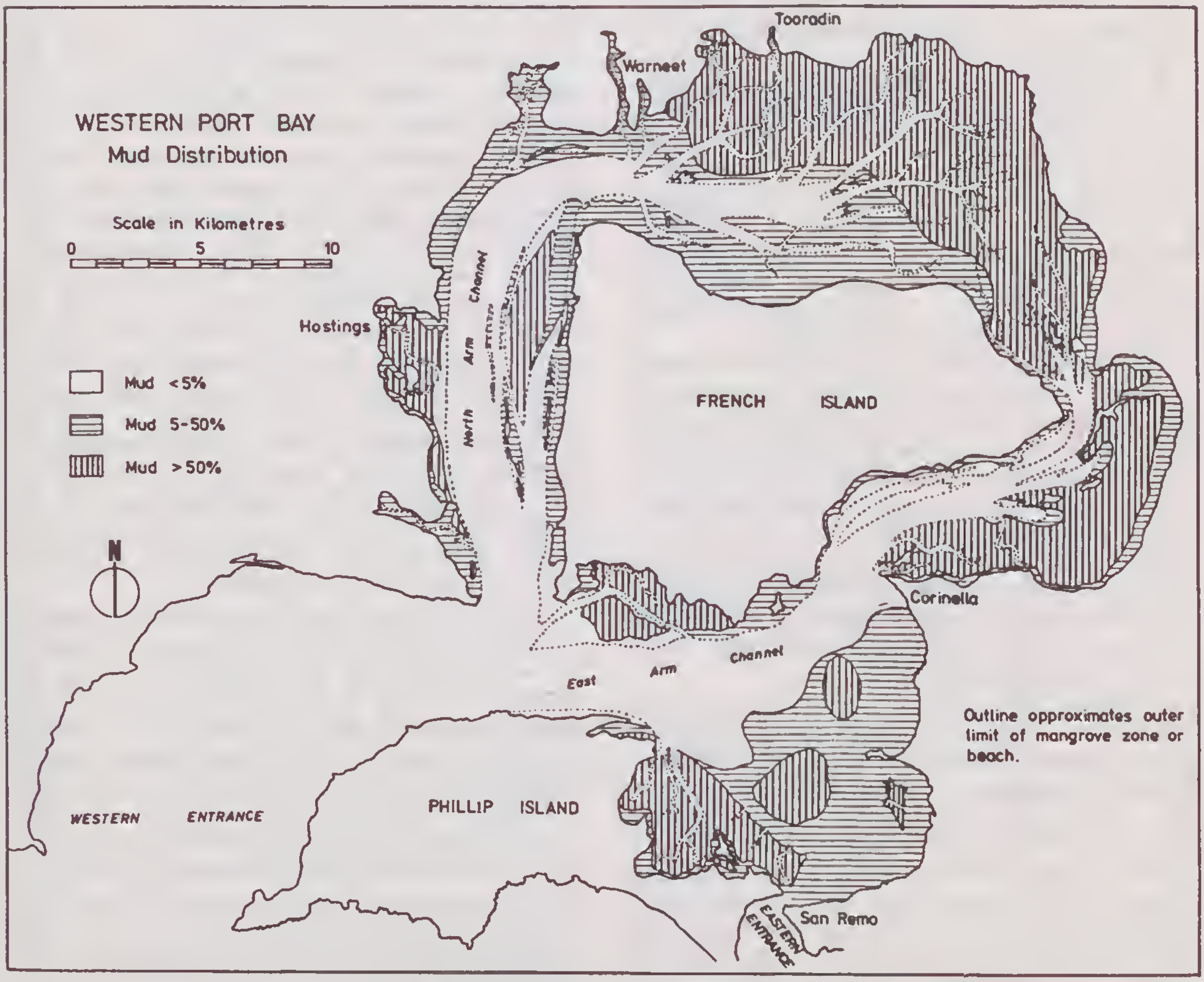

FIG. 8—Distribution of Mud, Westernport Bay.

medium sand prevail. For the East Arm, all samples had a mean size in the medium sand range, indicating relative uniformity throughout the length of the channel. In detail, however, the mean grain sizes may show rapid areal variation and no simple distribution pattern, or correlation with depth or with other controls has been made (Fig. 7).

In the Bay as a whole, and even in the channels, it is striking that the most frequently occurring mean size is medium sand (especially after making qualitative allowance for the relatively higher biogenic carbonate content in the coarser sand fractions). This, together with generally moderate to good sorting values, indicates that grain sizes close to medium sand form an important component of the population (instead of reflecting a wide spread between extreme sizes). This is further confirmed by the percentage of medium sand in the samples. The average was approximately 40%. The second-highest percentage was the fine sand component, in keeping with the prominence of fine sand mean sizes shown in Table 2.

SEDIMENT PARAMETERS AND RELATIONSHIPS

Binary scatter plots of mean grain size against sorting and skewness are shown in Figs. 10a, b, and three classes are differentiated (less than 5% mud; 5-30% mud; more than 30% mud). The dashed lines delineate the majority of samples having less than 5% mud from the other two classes.

The 'less than 5% mud' is essentially the channel population, with sizes ranging from very fine sand to a well-defined coarse sand maximum, sorting becoming progressively poorer with increasing mean size. Almost 80% of this population shows negative (coarse) skewness, up to −0·6, with only a few samples showing positive values greater than 0·2. Poorer sorting with increasing size, together with the coarse-skewed character, suggests that channel sediments contain, in addition to the dominant medium (to fine) sand population, coarser material, concentrated as a terrigenous or biogenic lag.

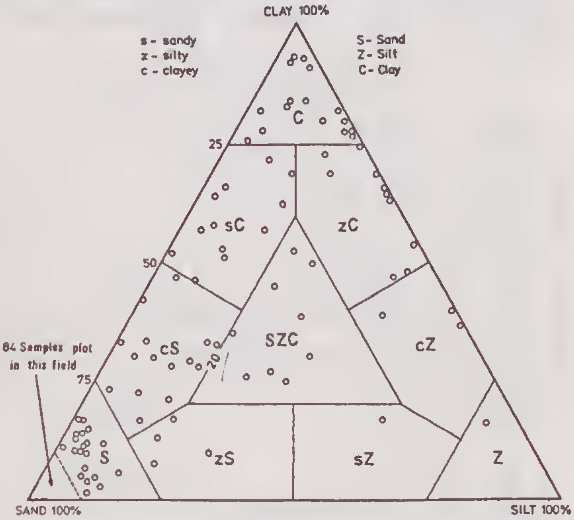

FIG. 9—Textural composition of Westernport Bay sediments.

TABLE 2

Distribution of mean grain sizes (based on sand plus silt fractions)

	All Samples	*Trunk Channels Only*
GRANULE	1	1
SAND		
Very coarse	2	1
Coarse	22	15
Medium	62	35
Fine	36	6
Very fine	19	—
SILT	7	—
	149	58

Samples from banks and tidal flats, etc. are included in both the '5-30%' and 'more than 30%' mud groups, between which no obvious differentiation can be made. Together, however, they show contrasts with channel sediments. Their maximum mean grain size is finer (medium sand) which, together with the marked trend toward negative (fine) skew reflects both lack of high energy and admixing of fines. Many of the samples are well-sorted, but the relationship between mean size and sorting is confused. Generally, the more poorly-sorted sediments appear to be those with finer mean grain size, the converse of the channel sediments. There is, however, a large scatter, and for a given sorting value, some samples show finer, and some coarser mean size. This probably reflects local variations in energy, supply, and bioturbation mixing, and hence a varying degree of incorporation of fine muddy sediment with the medium (to fine) sand population.

DISTRIBUTION OF MUD (SILT and CLAY)

Silt is apparently relatively deficient in Westernport Bay. Only seven samples had a mean grain size in the silt range and sand-silt-clay ratios (Fig. 9) show a strong emphasis on sand and clay. Only sixteen samples contained more than 30% silt, with only four having more than 50%.

Mud percentage data has been grouped as 'Less than 5% mud', '5-50% mud', 'More than 50% mud' (Fig. 8). Although a different class limit from the parameter plots (30% instead of 50%) has been used, this has no significant effect (only 13 samples occur between 30% and 50%).

Westernport Bay shows an overall outward trend of decreasing mud percentage, particularly well demonstrated by the Tooradin Tidal Flats, although the nearby Post Office Tidal Flats show low mud content (e.g. Locality 430—12% mud). One exception to this general trend is found within the East Arm Embayment Plain, which is mud-rich as a result of declining sand transport towards its deeper, more offshore parts.

Areas of 'less than 5% mud' lie deeper and further offshore, generally in the channels and other high-energy sandy zones, where there is either relatively strong winnowing or lack of mud for admixture. The limit of 5% mud was chosen, rather than zero, to allow for mud accumulation which occurs in the high-energy zones by settling of suspended sediment, and by transport, particularly from tidal flats, of sand-size biogenically pelleted mud, and of sand- and pebble-size eroded mud clasts. Mixing by bioturbation of discretely-deposited sands and clay-rich sediments is also locally important in producing muddy sediments.

Mud distribution is unlikely to indicate mud sources, but rather is more indicative of areal and bathymetric energy conditions, related especially to the time distribution of velocity within ebb and flood tidal cycles, and to maximum velocity. Deposition by 'settling lag' (van Straaten & Kuenen 1958) can occur by landward movement during settling, late in the flood-tide phase and at slack water, of suspended sediment. Some of this may be retained on the substrate as a result of its cohesion ('scour lag'). Shoreward movement and deposition by settling lag is most likely in the tidal flats, but local mud accumulation can occur even in channels.

The baffling, sediment trapping, and binding role of seagrass is important. The grassed areas vary in their substrate type and in their ability to retain sediment, and the presence of grass is not a simple indicator of the presence of trapped mud. Sandy substrates (either fixed or mobile), and stable muddy substrates developed initially under suitably low-energy conditions, may also carry grass. The area south of Stony Point (Locality 443, Hanns Inlet—100% mud) for example probably would not have accumulated mud without the presence of grass. As another example, the grassed areas on the Peck Point Tidal Flats show both trapping (mud) and non-trapping conditions (sand) within close proximity to each other.

SEDIMENT MOVEMENT AND DEPOSITION PATTERNS

One of the aims of the sedimentological studies of Westernport Bay has been to establish patterns of sediment movement and deposition. Data has been obtained from the individual morphological units and their sediments, by observing:

—Position, morphology and behaviour of sediment bodies such as washover sands, the longshore movement of the Inshore Marginal Sandy Zone and various types of ebb-tide and flood-tide constructed features.

—Orientation and behaviour of bedforms on sandy substrates, such as mega-ripples and sand waves, as on Middle Bank and the Freeman Point Banks.

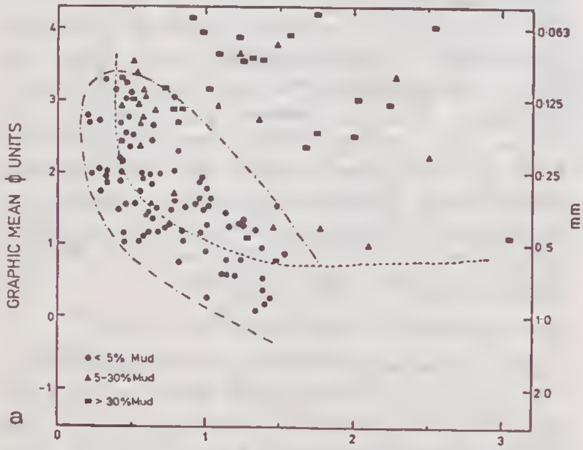

FIG. 10a—Binary scatter plot. Mean grain size versus sorting.

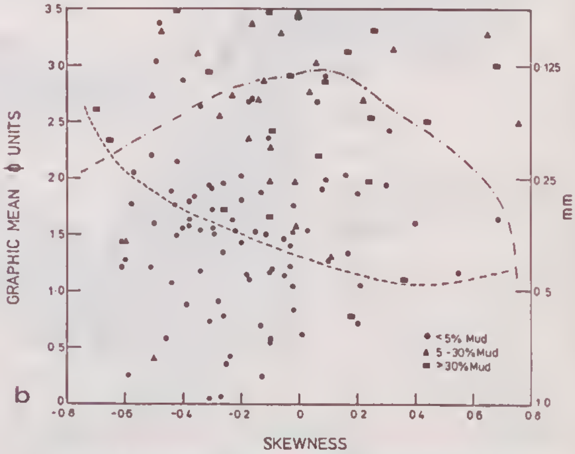

FIG. 10b—Binary scatter plot. Mean grain size versus skewness.

—Variations in grain size, and in other parameters. These can only be attributed to hydrodynamic transport after consideration of other variables such as the distribution of relic sediment, as in the anomalous sandy northwestern segment of Westernport Bay.

—Variations in composition of sediment derived from various onshore and offshore sources in the Westernport system, as in the depositional areas of Bass River sediments, and landward sediment transport onto tidal flats.

—Distribution and movement of suspended sediment in the water mass.

Broad bedload sediment movement patterns have been interpreted for the trunk channels and for more local paths, and these are shown in Fig. 1. The vectors represent the net direction suggested by various lines of evidence. They do not imply unidirectional transport, but indicate the dominant direction.

Although the bedload sedimentation patterns are generalized, they demonstrate ebb-flow and flood-flow differentiation. For example, general alternation of the path of flood-flow, progressively on either side of the Western Entrance and East Arm Channels, is matched by an analogous ebb-flow pattern. The prominent cross-channel sedimentation asymmetry reflects these patterns. Flood dominance occurs generally across Middle Bank along the Cowes Bank, and possibly along the southern margin of the East Arm Channel towards Corinella and then swings across to the Freeman Point Banks area. Complex differentiation occurs in the Queensferry area and includes apparent counter-clockwise patterns. Ebb-dominance areas include the Corinella and Peck Point Tidal Flats. Flow from the latter may join with the flow from the ebb-dominant Middle Spit Channel on the eastern side of North Arm, and leads to the head of the Western Entrance Channel.

It is notable that prominent sand complexes (e.g. Sandy Point/Middle Bank, Cowes Bank) are associated with flood-tide dominant (and wave-affected) areas, but that ebb-dominant zones tend to be mud-rich, in part because of the lack of sand supply from the embayment-head areas.

The moulding of the major and minor morphological features of the Bay is closely controlled by these and other bedload transport patterns which are shown in more detail in Fig. 1, and referred to in the discussion of individual morphological units.

CONCLUSION

The distribution in Westernport Bay of such a large number of varied morphological units emphasizes the relationship between Quaternary evolution, morphology, distribution of sediment type, and physical and biological processes. This may best be appreciated by summarizing the style of the rapid variability seen in the morphology of the Bay.

1. *Rapid variability within a local area, essentially an individual morphological unit,* illustrated by the inclusion within the Hastings Bight Tidal Flat of overwash sands from the trunk channel, of eroded coquinas, of grassed fine-grained tidal flats, and the intimate juxtaposition of the Inshore Marginal Sandy Zone, backed in turn by Mangrove and Salt Marsh zones.
2. *Gross regional variation between immediately adjacent units,* illustrated by the contrasts between the lagoon-sand bank complex of the Rhyll Swamp, The Nits and the Cowes Bank; the clay-dominant Churchill Tidal Flats; and the sand sediment influx area of the Bass delta, all of which fringe the mud-rich East Arm Embayment Plain.
3. *Gross variation in sediment type between units having similar morphology and dynamics,* illustrated by the contrast between the muddy Tooradin Tidal Flats and the sandy Post Office Tidal Flats, hydrodynamic causes being subordinate to the geological evolution of the area.

All the sediment characteristics of Westernport Bay lead to the conclusion that the dominant sediment population, found in a variety of environments of different energy, consists of medium sand and fine sand, mixed with varying proportions of clay. This may indicate important provenance aspects of the Westernport system.

Current velocities required to initiate transport of fine to medium sand are minimal compared with the threshold velocities required for coarser sand and for cohesive finer sediment (Hjulstrom 1935). The concentration of medium and fine sands in the bedload of the Bay may therefore be due to winnowing by inward re-working, with consequent differentiation of the relic sediment developed during the late Pleistocene to early Holocene. Overall winnowing has probably been controlled by the hydrodynamic regime, particularly that of the channels. Only local hinterland sources such as the Bass River contributed minor fine-grained sediment.

The potential sedimentary material developed during Phase 3 of the Quaternary probably had an overall compositional bias towards quartz and clay composition, the relative lack of silt-size materials possibly reflecting the very limited source areas of Lower Palaeozoic sedimentary rocks. The T_1, and T_2 sediments of the Bass system not only illustrate the likely silt deficiency of the offshore Quaternary relic sediment of equivalent age, but also indicate the type of sediment to be expected by direct present-day contribution from Mesozoic and Tertiary sedimentary rocks. The extensive flanking basalts also contribute clays rather than silts. The coarser sands and gravelly sediments which are found in relatively minor amounts in channels may therefore be lag deposits and in some cases are demonstrably immobile in the present dynamic regime. Some gravels may reflect transport concentration into small local zones of higher tidal velocities.

Landward transport and deposition of clay-rich suspended sediment by tidal processes, aided by biological and mechanical factors, have accentuated the marked overall inward-fining sediment gradient of Westernport Bay, culminating in the extensive embayment-head tidal flats. The frequent reference to the various channel-margin, isolated and embayment-head intertidal areas as 'mud-flats' tends to obscure the significance of the variation in substrate sediment type actually found in these environments.

Generally the coarsest sediments are found in the coarse sandy and gravelly zone along the southern Victorian coastline, with grain size decreasing outwards into Bass Strait. This is probably a function of lower-energy conditions in deepening water, a lower degree of winnowing, and increasing distance from source areas.

Morphological and sediment distribution evidence points strongly to specific net transport paths in the Bay, dominated by tidal energy, with net ebb-tide flow and flood-tide flow often differentiated. Confirmation and elaboration of these paths will require more detailed measurements of both short-term hydrodynamic and bedload and suspended sediment movements, and also studies of the structure and composition of earlier-deposited sediment bodies, to provide long-term data relating to the prevailing movement patterns.

Variability of characteristics and processes is one of the very important features of Westernport Bay, and extrapolation of data from one morphological unit to another, even over relatively short distances, could be hazardous. The design of sampling programmes, and, in particular, generalizations regarding the behaviour of the Bay, must be based on appreciation of the complex interrelationships between its various parts, and the solution of problems relating to any specific part will need specific data relating to the processes of the relevant morphological unit.

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REFERENCES

Barton, C. M., 1974. *Interim Report on P.W.D. Westernport Seabed Investigation. Project notes and log sheets.* Division of Applied Geomechanics, CSIRO.

Beasley, A. W., 1966. Bottom Sediments, Port Phillip Survey 1957-1963. *Mem. nat. Mus. Vict.* 27: 69-105.

Bird, E. C. F., 1973. Physiographic changes on sandy shorelines in Victoria (Australia) within the past century. *I.G.U. Working Group on the dynamics of shoreline erosion, Discussion Paper.* Department of Geography, University of Melbourne.

Bishop, I. D. & Cresswell, L. A., 1972. The Westernport Earthquake of 6th July, 1971. *Proc. R. Soc. Vict.* 85: 70-1.

Bowler, J. M., 1966. The Geology and Geomorphology, Port Phillip Survey 1957-1963. *Mem. nat. Mus. Vict.* 27: 19-67.

Brennan, R. D., 1972. Quaternary studies of two Westernport environments. Unpub. B.Sc. Hons. Report, Geology Department, University of Melbourne.

Davies, P. J. & Marshall, J. F., 1973. BMR Marine Geology Cruise in Bass Strait and Tasmanian waters—February to May 1973 *Bur. Min. Resour. Aust. Rec.* 1973/134.

Edwards, A. B., 1942. The San Remo Peninsula. *Proc. R. Soc. Vict.* 54: 59-76.

Folk, R. L., 1968. *Petrology of Sedimentary Rocks.* Hemphill's, Austin, Texas.